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MASTER CURVE DETERMINATION OF THE FRACTURE TRANSITION IN A CSA 350WT PLATE AND WELD

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ETERMINATION OF THE FRACTURE A CSA350WT PLATE AND WELD

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Abstract

The DREA Dockyard Laboratory Pacific (DL(P)) has an on-going requirement to determine the fracture toughness of ship steels and welds in the ductile to brittle transition temperature range. ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" can be used to generate transition master curves.

CSA G21 350WT is a ferritic steel used extensively in the hulls of the Canadian Navy's Halifax class frigates. An earlier contract demonstrated that valid results could be obtained from 350WT L-T oriented specimens using the ASTM test method. This program was subsequently expanded to investigate the effect of plate orientation (L-T and T-L) and loading rates (quasi-static and intermediate) on both 350WT plate and welds. This work was supplemented by experiments at DL(P) using a drop tower to achieve high deformation rates. The test program was very successful in quantifying the fracture toughness over the temperature range of interest. Both the plate and submerged arc weld are very tough, and have very low reference temperatures, suggesting that there is a high resistance to brittle fracture in this material. This data will be useful for damage assessment and fitness-for-purpose assessments in repair situations

Résumé

Le Laboratoire de chantier naval Pacific (DL(P) du CRDA a actuellement besoin de déterminer la ténacité des aciers et des soudures des navires dans la plage de températures de transition de ductile à fragile. On peut utiliser la méthode d'essai ASTM E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" pour produire des courbes principales de transition.

L'acier CSA G21 350WT est un acier ferritique très utilisé dans la coque des frégates de la classe Halifax de la marine canadienne. Une étude donnée en sous-traitance a permis de confirmer que la méthode ASTM permettait d'obtenir des résultats valables à partir d'éprouvettes orientées de 350WT L-T. Il y a eu par la suite une extension de ce programme pour étudier l'effet de l'orientation de la plaque (L-T et T-L) et les taux de chargement(quasi-statique et intermédiaire) sur la plaque de 350WT et sur les soudures. Ces travaux ont été complétés par des expériences au DL(P) où des taux de déformation élevés ont été atteints dans une tour de chute. Ce programme d'essai a été un grand succès pour quantifier la ténacité sur la plage de températures visée. La plaque et la soudure à l'arc immergée ont toutes deux une ténacité élevée et des températures de référence très basses, ce qui porte à croire que le matériau a une bonne résistance à la rupture fragile. Ces données seront utiles pour évaluer les dommages et pour des évaluations d'applications adaptées à un usage en cas de réparation.

Executive Summary

The primary method for avoiding brittle fracture in welded structures such as warship hull is to prevent crack initiation by using high standards of quality control and workmanship during construction, particularly in welding. However, given normal shipyard limitations, some welds will likely have local regions of low toughness or small crack like defects. These could threaten the integrity of the structure if it encountered a suitably high combination of applied loading, stress concentration, and residual stresses. This will necessitate pessimistic estimates of tolerable flaw size unless the material toughness can be accurately quantified.

In recent years however, the availability of better instrumentation and more sophisticated structural analysis has improved small specimen test methods for toughness determination. This report describes toughness determined from a Canadian ship steel using a recently developed "master curve" methodology. This procedure has been successful in generating useful data for structural integrity assessments. The results suggest that there is a low risk of brittle fracture of the 350WT plate and a submerged arc weld under normal ship operating conditions. Future work will include measurements on additional plate and welds used in Canadian frigates, and on candidate steels for future construction and repair.

Sommaire

La première méthode pour éviter une fracture fragile des structures soudées, comme la coque d'un navire de guerre. consiste à empêcher la formation de fissures en appliquant des normes élevées de contrôle de la qualité et de qualité de fabrication pendant la construction et en particulier pendant le soudage. Cependant, à cause des limites imposées par les chantiers navals, certaines soudures risquent de présenter des zones localisées de faible ténacité ou des défauts comme des micro-fissures. Cela pourrait menacer l'intégrité de la structure si la combinaison des charges appliquées, de la concentration des contraintes et des contraintes résiduelles est suffisante. Cela nécessitera des évaluations pessimistes de la dimension tolérable des défauts, sauf si la ténacité du métal peut être quantifiée avec précision.

Ces dernières années cependant, grâce à une meilleure instrumentation et une analyse structurale plus perfectionnée, les méthodes d'essai pour la détermination de la ténacité des petites éprouvettes ont été améliorées. Ce rapport traite de la détermination de la ténacité de l'acier d'un navire canadien à l'aide de la méthodologie récente des "courbes principales". Cette méthode a permis de produire des données utiles pour évaluer l'intégrité structurale. D'après les résultats, le risque de fracture fragile est faible pour les plaques de 350WT et une soudure à l'arc immergée dans des conditions normales de navigation. Les futurs travaux porteront sur des mesures d'autres plaques et soudures sur les frégates canadiennes et sur des aciers pouvant être utilisés pour des constructions et des réparations futures.

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F - 350WT Weld, Quasi-Static Loading Rate
G - 350WT Weld, Intermediate Loading Rate

1.0 INTRODUCTION.

Operational demands imposed on Canadian warships require materials which provide high structural integrity. Improved fracture control procedures for material selection are needed to reduce maintenance costs and maximize operational readiness. The Dockyard Laboratory Pacific (DL(P)) has an on-going requirement to determine the fracture toughness of ferritic steels and welds in the ductile to brittle transition temperature range. ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" can be used to generate transition curves characterized by a reference temperature calculated using maximum likelihood statistics at a K_{Jc} toughness value of 100 MPa$\sqrt{m}$.

CSA G21 350WT is a ferritic steel used extensively in the hulls of the Canadian Navy's Halifax class frigates. A Phase I contract (W7708-7-0705/001/XSA) demonstrated that valid results could be obtained from 350WT L-T oriented specimens using the ASTM standard (Steel Transition Fracture Toughness Reference Temperature Determination, DREA CR 98/439).

The DL(P) sponsored program was subsequently expanded to Phases II and III. and this report describes Phase II of this program. The objective was to investigate the effect of plate orientation (L-T and T-L) and loading rates (quasi-static and intermediate) on 350WT plate and weld specimens. including comparison with the Phase I results. This work was supplemented with experiments at the DREA Dockyard Laboratory (Pacific) (DL(P)) using a drop tower to achieve high deformation rates. Engineering Material Research carried out these fracture toughness measurements under research and development contract W7707-8-6178/001/HAL.

2.0 TEST PROCEDURE.

The 15 mm thick 350WT plate from which the specimens were machined at DL(P) had the chemical composition shown in Table I, and the test conditions are presented in Table 2. Two displacement rates (0.05 and 6 mm/s) were used to give average elastic stress intensity rates of 4 MPa$\sqrt{m}$/s (quasi-static) and 300 MPa$\sqrt{m}$/s (intermediate) respectively. The DL(P) drop tower tests were done at 1 m/s with a stress intensity rate averaging 6×10^4 MPa$\sqrt{m}$/s. The room temperature yield strength of the steel plate was 450 MPa, while the Charpy V-notch energy was 120 Joules at -40°C (L-T orientation). The single edge notched bend specimens had nominal dimensions of 15 x 30 x 130 mm. The submerged arc butt welded plate had a nominal thickness of 10 mm. Most of the weld bend specimens were nominally 10 x 30 x 130 mm. For comparison, an additional set of 10 x 20 x 130 mm weld specimens was tested at quasi-static rates.

Tensile test properties at each test temperature were needed for data qualification purposes. Subsize tensile specimens with threaded ends that met ASTM E8-98 requirements, were

machined from 350WT steel blanks supplied by DL(P). The yield strength (0.2% offset), ultimate tensile strength and elongation to fracture were determined experimentally at both loading rates. There was insufficient weld for full weld tensile specimens. However, a quasi-static full-weld tensile value of 505 MPa at room temperature was supplied by DREA. From this result, a weld tensile value appropriate to the test temperature and loading rate could be estimated using ASTM E1820-99 Annex 13 "Method for Rapid Loading K_{Ic} Determination", Section A13.6.6.

This investigation employed a 100 kN capacity servo-hydraulic load frame equipped with a stainless steel three point bend fixture. The ASTM E1921-97 procedure was followed throughout the test program. A personal computer was used to control the load frame and acquire four channels of data. A cold box with 100 mm thick insulation allowed tests to be conducted at temperatures as low as -100°C within ±2°C. The specimen temperature was monitored by two thermocouples mounted 5 mm on each side of the specimen starter notch. Initially the thermocouple wire pairs were twisted together and spot welded to the specimen surface. A forthcoming revision to the ASTM 1921 standard recommends that each thermocouple wire be spot welded to the specimen surface and this practice was subsequently followed. A temperature controller cycled a solenoid valve to regulate the flow of nitrogen from a cryogenic dewar into the cold box. Load was monitored using the crosshead load cell, while specimen crack mouth opening displacement (CMOD) and load line displacement (LLD) were measured using a clip gauge and extensometer respectively. The test temperature was selected initially using energy values from Charpy V-notch specimen tests per the guidelines provided in ASTM E1921-96, and modified as appropriate according to the results from trial tests. The standard requires that cleavage fracture occur at this test temperature, and the target median K_{Jc} is 100 MPa$\sqrt{m}$. A minimum of six replicate specimens must be tested, and provision was made for up to six more in the event that some of the tests failed to generate a valid result.

Specimens were pre-cracked to a nominal a/W of 0.5 and then side-grooved 10% of the thickness on each side. The bend specimens were cooled to the temperature of interest and then dwelled for 3-5 minutes before the test was started. Plots of load versus LLD were constructed to permit J-integral calculation using the expressions provided in the standard. Given the highly statistical nature of cleavage initiation, in any given set of specimens, there can be major differences in the amount of non-linearity obtained in these curves before an instability was observed. Figure 1 illustrates four possible categories, arbitrarily defined, although only the first three types were observed during these tests. In the following sections the amount of plasticity observed for each test is indicated using Types I-III to describe elastic, elastic-plastic, and near limit load behaviour respectively.

For each specimen a K_{Jc} value was calculated from the J value at the onset of cleavage. The procedure requires a minimum of six replicate tests with additional tests being required in the event that values outside a defined range, or otherwise invalid, are encountered. Following completion of the fracture test, the broken halves of the specimen were warmed to approximately 50°C to remove condensation from the fracture surfaces

and were then air cooled. Crack lengths were measured with an optical travelling microscope using the nine point average procedure of ASTM E1921-97. The nine crack length measurements must not differ from the average by more than 7% or 0.5 mm, whichever is larger.

The required cleavage event must occur prior to reaching the K_{Jc} capacity the specimen given by the equation:

$$K_{Jc(limit)} = \sqrt{(E\, b_o \sigma_{ys} / 30)} \qquad (1)$$

Where E is the elastic modulus, σ_{ys} is the yield strength at test temperature and loading rate, and b_o is the specimen remaining ligament.

The transition temperature curve was determined using the maximum likelihood procedure provided in the standard, and a typical curve with upper (5%) and lower (95%) tolerance bounds is illustrated in Figure 2.

3.0 RESULTS.

3.1 Tensile Test Results.

Tensile load versus displacement plots are given in Appendix A. Yield strength, ultimate tensile strength, and elongation are shown in Table 3. Failure of the parent material in the cross-weld specimens indicated the weld is stronger than the plate. Plate tensile results were used with equation (1) to determine the specimen K_{Jc} capacities listed in Table 4.

3.2 K_{Jc} Results.

For each set of test specimens master curve calculations are summarized in Tables 6-20 Crack size determinations and detailed K_{Jc} calculations, are tabulated in Appendix B. The individual load-load line displacement curves generated during the fracture tests are shown in Appendices C - H.

3.2.1 K_{Jc} Results - 350WT Plate.

a) T-L Orientation - Quasi-Static Loading Rate (Tables 5-8, B1-B4, Appendix C).

Exploratory tests were carried out at -60°C and -70°C. From these results the test temperature for the remaining specimens was selected to be -50°C. The results are shown in Table 5. In the -50°C tests, the force at which an abrupt crack instability occurred varied

between 17 and 19 kN, and the corresponding range of K_{Jc} was 97 to 215 MPa√m. Cleavage was observed on all of the specimen fracture surfaces and all failed below the K_{Jc} upper limit of 239 MPa√m. Crack front straightness met E1921-97 requirements. Thickness adjusted (1T) K_{Jc} values were used to determine the median K_{Jc}(1T) of 147 MPa√m and reference temperature of -76°C (Table 6). The corresponding transition temperature curve with tolerance bounds is shown in Figure 3. The roman numeral next to each data point indicates the type of load versus displacement behaviour as defined in Figure 1, which for the -50°C specimens was either Type II or III. In Type III behaviour cleavage occurred close to specimen limit load, which was estimated to be about 18 kN.

The 147 MPa√m median value indicated that the test temperature of -50°C was higher than desired. A test temperature of -60°C or -70°C would have produced a median value closer to the E1921-97 recommended 100 MPa√m. Consequently a supplementary set of six specimens was tested at -76°C and these results are shown in Table 7. The K_{Jc} values varied from 91 to 166 MPa√m, a smaller range than that observed at the higher temperature, and the material behaviour varied from type I to III. The median K_{Jc}(1T) and reference temperature were 112 MPa√m and -85°C respectively (Table 8). The transition temperature curve is shown in Figure 4. There was a 9°C difference between the two reference temperatures. The standard deviation on the estimate of these T_o values was about 8°C.

b) T-L Orientation - Intermediate Loading Rate (Tables 9-12, B5-B8, Appendix D).

All of the T-L intermediate loading rate experiments were carried out at -50°C and these results are presented in Table 9. All of the specimens showed a cleavage instability, and the fracture force and K_{Jc} values varied from 14 to 19 kN and 70 to 121 MPa√m respectively. None of the experiment results exceeded the K_{Jc} limit of 235 MPa√m or the crack front straightness requirement. The transition curve analysis in Table 10 produced a K_{Jc}(1T) median and T_o of 87 MPa√m and -39°C respectively. The transition temperature curve and tolerance bounds are shown in Figure 5. A lower scatter was noted in this data with primarily Type I or II behaviour. The intermediate loading rate reference temperature was 37°C higher than the quasi-static result. An additional six specimens were evaluated at the -39°C reference temperature and these results are shown in Tables 11 and 12. The median K_{Jc}(1T) value of 168 MPa√m and reference temperature of -74°C were quite different from the preceding results and the behaviour was predominantly Type III. As can be seen in Fig. 6, this inevitably produced a wider spread of data about the median curve than at -50°C. Review of the equipment setup, transducer and temperature calibration, etc. did not reveal any causes which could account for this large difference. It is not clear whether a change in material behaviour occurs in this temperature range but it is suggested that additional specimens be evaluated in the -50°C to -30°C range to fully characterize the material behaviour at this rate.

c) L-T Orientation - Intermediate Loading Rate (Tables 13-14. B9-B10, Appendix E).

These tests were conducted at -88°C and the results are shown in Table 13. The fracture load varied from 8 to 26 kN and the K_{Jc} values ranged from 40 to 174 MPa$\sqrt{m}$, showing either Type I or II behaviour. None of the results exceeded the K_{Jc} limit of 260 MPa$\sqrt{m}$. However analysis of the first 9 samples indicated that two K_{Jc} results (40 and 48 MPa$\sqrt{m}$) fell below the 2% tolerance bound. Five additional specimens were used to reduce the effect of these low values on the K_{Jc}(1T) median value. The ASTM E1921-97 standard allowed the two low values be classed as outliers and be discarded. However, a proposed revision to the E1921 standard requires the low values to be included in the determination of the reference temperature. The latter approach was followed here. This resulted in a median K_{Jc}(1T) value of 98 MPa$\sqrt{m}$ and a reference temperature of -86°C (Table 14). The transition temperature curve and tolerance bounds are plotted in Figure 7. The intermediate loading rate produced a +14°C shift in reference temperature relative to the quasi-static result of 100°C from the previous investigation.

The combined L-T and T-L results for the quasi-static and intermediate loading rates are presented in Figure 8. The quasi-static L-T results from the previous (Phase I) study are included. Pairing the material behaviour type with the data point is useful because it provides an indication of the amount of plasticity present at the onset of cleavage. Not surprisingly. the Types I. II and III failures generally fall within specific ranges of K_{Jc}. The variation in the T-L intermediate results is shown at the right of the plot by the open square symbols.

3.2.2 K_{Jc} Results - Weld.

a) Quasi-Static Loading Rate (Tables 15-18. B11-B14, Appendix F).

The submerged arc welded 12 mm thick 350WT plate was produced for DREA by St John Shipyards. From these DL(P) supplied 10 mm thick bend specimens through thickness notched at the weld centreline with W = 30 except for one batch with a nominal W of 20 mm.

The results obtained from specimens with W = 30 mm are shown in Table 15. Two exploratory specimens were evaluated at -40°C and -50°C before selecting -60°C to be the temperature for the K_{Jc} evaluation. Initial analysis of the first 9 results revealed one outlier. and the K_{Jc} limit of 252 MPa$\sqrt{m}$ was exceeded by 4 other specimens. An additional 3 specimens were then tested. The fracture loads and K_{Jc} values varied from 11 to 14 kN and 86 to 290 MPa$\sqrt{m}$ respectively. The high values necessitated using the E1921 data censoring procedure. whereby the K_{Jc} limit of 252 MPa$\sqrt{m}$ is substituted for any higher results. A median K_{Jc}(1T) value of 188 MPa$\sqrt{m}$ and a reference temperature of -103°C were calculated (Table 16). The transition temperature curve is shown in Figure 9. The behaviour is mainly Type II/III with a single Type I, and a correspondingly large scatter.

The smaller specimens were evaluated at -70°C (Table 17). Only one result exceeded the K_{Jc} limit of 202 MPa√m. The fracture loads and K_{Jc} values varied from 10 to 13 kN and 96 to 277 MPa√m respectively. The data censoring procedure was used to determine a median K_{Jc}(1T) of 141 MPa√m and a reference temperature of -94°C (Table 18). Cleavage occurred near limit load for these specimens, i.e, type III. The transition temperature curve is shown in Figure 5. A difference of 9°C exists between the reference temperatures from the specimens with the two different widths.

b) Intermediate Loading Rate (Tables 19-20, B15-B16, Appendix G).

The bulk of the intermediate loading rate specimens were evaluated at -70°C after exploratory testing at -50°C, -60°C, and -80°C. The maximum load at fracture and The fracture loads and K_{Jc} values varied from 7 to 15 kN and 53 to 183 MPa√m respectively (Table 19). None of the -70°C results exceeded the K_{Jc} limit of 270 MPa√m or the crack front straightness requirement and an abrupt crack instability was observed in all cases. The results of the 8 valid tests yielded a median K_{Jc}(1T) value of 104 MPa√m and a reference temperature of -73°C (Table 20 and Figure 11). The intermediate loading rate resulted in a +38°C shift in reference temperature relative to the quasi-static result. The combined weld results are plotted in Figure 12. The weld is very tough with reference temperatures that are lower than plate values.

4.0 CONCLUSIONS.

The ASTM E1921-97 test method has been used to determine the ductile to brittle fracture transition behaviour of a CSA G21 350WT plate and submerged arc weld at both quasi-static and intermediate loading rates. In general the test program was very successful in providing valid results. and quantifying the fracture toughness over the temperature range of interest. Both the plate and weld are very tough, and have very low reference temperatures. suggesting that there is a high resistance to brittle fracture in this material. This data will be useful for damage assessment and fitness-for-purpose assessments in repair situations. Phase III of this work will include the assessment of the higher strength ASTM A517 steel and weld. which is also used in the hull of the Halifax class frigates. The master curve technique should also be valuable in the assessment of marine steels for future naval construction.

Material	Orientation	Loading Rate	Test Temperature °C
350WT Plate	T-L	Quasi-Static	-50
	T-L	Quasi-Static	-76
	T-L	Intermediate	-50
	T-L	Intermediate	-38
	L-T	Intermediate	-88
Weld		Quasi-Static	-60
Weld (20x10)		Quasi-Static	-70
Weld		Intermediate	-70

Table 1 - 350WT Plate and Weld Test Conditions.

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Ti	Al
0.16	1.38	0.009	0.005	0.28	0.019	0.21	0.018	0.009	0.07	0.002	0.009	0.036

Table 2 - 350WT Plate Chemical Composition.

Specimen ID	Rate QS or Int.	Temp. °C	0.2% PS MPa	UTS MPa	Elong. %
T350-5 T-L	QS	-50	510	668	27
T350-6 T-L	QS	-50	516	677	28
T350-3 T-L	I	-50	561	699	28
T350-4 T-L	I	-50	574	696	26
T350-1 L-T	I	-88	635	728	22
T350-2 L-T	I	-88	622	738	25
T350-7 W	QS	-60	504	606	26 (P)
T350-8 W	QS	-60	504	600	25 (P)
T350-9 W	I	-70	520	638	22 (P)
T350-10 W	I	-70	-	651	25 (P)

(P) – fractured in parent material.

Table 3 - 350WT Plate and Weld Tensile Test Results.

Orientation	Rate	Temp. °C	0.2% PS MPa	b_0 mm	K_{Jc} Limit MPa√m
T-L	QS	-50	513	16.0	239
T-L	I	-50	568	16.0	235
L-T	I	-88	629	16.0	260
Weld	QS	-60	590	16.0	252
Weld	QS	-70	603	10.0	202
Weld	I	-70	678	16.0	270

E = 202 GPa

Table 4 - Specimen K_{Jc} Capacities.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
G350-7	-50	II	17.4	0.4	0.51	97	87
G350-4	-50	II	17.4	0.5	0.51	99	89
G350-8	-50	III	19.4	0.8	0.51	155	138
G350-10	-50	III	18.2	0.8	0.53	165	147
G350-5	-50	III	19.0	0.9	0.50	169	151
G350-11	-50	III	18.8	1.1	0.51	205	182
G350-9	-50	III	19.2	1.2	0.52	215	191
G350-1	-60	III	17.9	0.9	0.53	174	-
G350-2	-60	II	15.5	0.5	0.52	78	-
G350-12	-70	I	15.2	0.3	0.51	67	-

Table 5 - 350WT T-L Orientation - Quasi-Static Loading Rate (1).

Scale Parameter K_o = 157 MPa√m

Median K_{Jc} = 145 MPa√m

Reference Temperature T_o = -76 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 76)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 76)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 76)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 63)]

Table 6 - 350WT T-L Master Curve Analysis - Quasi-Static Loading Rate at -50°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
350X-1	-76	I	15.8	0.2	0.50	91	82
350X-5	-76	II	17.9	0.5	0.51	105	95
350X-2	-76	II	18.3	0.6	0.51	117	106
350X-3	-76	II	18.5	0.6	0.52	128	115
350X-6	-76	II	20.4	0.7	0.50	146	130
350X-4	-76	III	19.1	0.9	0.52	166	148

Table 7 - 350WT T-L Orientation - Quasi-Static Loading Rate (2).

Scale Parameter K_o = 121 MPa√m

Median K_{Jc} = 112 MPa√m

Reference Temperature T_o = -85 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 85)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 85)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 85)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 71)]

Table 8 - 350WT T-L Master Curve Analysis - Quasi-Static Loading Rate at -76°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
G350-20	-50	I	13.7	0.2	0.51	70	64
G350-23	-50	I	15.6	0.2	0.52	81	73
G350-24	-50	I	14.6	0.1	0.55	82	74
G350-18	-50	I	17.6	0.3	0.54	92	83
G350-16	-50	II	17.9	0.4	0.51	94	85
G350-15	-50	II	19.4	0.4	0.50	102	92
G350-22	-50	II	18.3	0.5	0.52	107	96
G350-13	-50	II	18.4	0.5	0.52	111	100
G350-19	-50	II	18.2	0.3	0.53	118	106
G350-17	-50	II	18.3	0.4	0.53	121	108

Table 9 - 350WT T-L Orientation - Intermediate Loading Rate (1).

Scale Parameter K_o = 93 MPa√m

Median K_{Jc} = 87 MPa√m

Reference Temperature T_o = -39 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 39)]$

Upper Tolerance Bound: $K_{Jc}(95\%) = 34.5 + 101.3 \exp[0.019 (T + 39)]$

Lower Tolerance Bound: $K_{Jc}(5\%) = 25.2 + 36.6 \exp[0.019 (T + 39)]$

Margin Adjusted Lower Bound Curve: : $K_{Jc}(LB) = 25.2 + 36.6 \exp[0.019(T + 28)]$

Table 10 - 350WT T-L Master Curve Analysis - Intermediate Loading Rate at -50°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
350X8	-38	II	18.4	0.6	0.52	119	107
350X7	-38	II	20.0	0.7	0.51	144	129
350TL17	-38	III	20.3	0.9	0.51	174	155
350X10	-38	III	20.3	1.0	0.51	222	197
350X9	-38	III	20.0	1.5	0.52	234	208
350TL16	-38	III	21.1	1.4	0.51	234	208

Table 11 - 350WT T-L Orientation - Intermediate Loading Rate (2).

Scale Parameter K_o = 183 MPa√m

Median K_{Jc} = 168 MPa√m

Reference Temperature T_o = -74 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 74)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 74)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 74)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 60)]

Table 12 - 350WT T-L Master Curve Analysis - Intermediate Loading Rate at -38°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
F350-12	-88	I	8.0	0.1	0.52	40	38
F350-9	-88	I	9.2	0.1	0.54	48	45
F350-1	-88	I	13.5	0.3	0.51	66	60
F350-4	-88	I	14.6	0.2	0.52	74	67
F350-13	-88	I	13.0	0.2	0.53	77	70
F350-14	-88	I	17.3	0.3	0.49	82	74
F350-2	-88	I	11.5	0.5	0.51	86	78
F350-17	-88	I	17.5	0.3	0.51	95	86
F350-8	-88	I	19.2	0.3	0.53	96	87
F350-16	-88	I	19.1	0.4	0.50	96	87
F350-3	-88	II	19.4	0.4	0.53	101	91
F350-5	-88	II	22.2	0.5	0.52	132	118
F350-11	-88	II	22.3	0.6	0.52	152	136
F350-15	-88	II	25.8	0.5	0.47	174	155

Table 13 - 350WT L-T Orientation - Intermediate Loading Rate.

Scale Parameter K_o = 105 MPa√m

Median K_{Jc} = 98 MPa√m

Reference Temperature T_o = -86 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 86)]$

Upper Tolerance Bound: K_{Jc} (95%) = $34.5 + 101.3 \exp[0.019 (T + 86)]$

Lower Tolerance Bound: K_{Jc} (5%) = $25.2 + 36.6 \exp[0.019 (T + 86)]$

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = $25.2 + 36.6 \exp[0.019(T + 77)]$

Table 14 - 350WT L-T Master Curve Analysis - Intermediate Loading Rate at -88°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
W350-2	-40	III	13.0	0.6	0.49	128	-
W350-10	-50	III	12.9	1.4	0.52	248	-
W350-8	-60	I	11.2	0.2	0.49	86	72
W350-24	-60	II	12.4	0.4	0.49	126	104
W350-11	-60	II	12.3	0.6	0.50	135	111
W350-44	-60	II	12.0	0.5	0.52	142	117
W350-14*	-60	III	10.9	0.9	0.56	184	-
W350-22	-60	III	14.1	1.3	0.49	229	186
W350-12	-60	III	13.7	1.3	0.49	245	198
W350-43	-60	III	14.8	1.7	0.47	260	210
W350-42	-60	III	15.0	1.8	0.46	270	218
W350-13	-60	III	12.9	2.0	0.53	289	233
W350-19	-60	III	12.0	2.0	0.55	290	234

* invalid crack length

Table 15 - 350WT Weld (W=30mm) - Quasi-static Loading Rate.

Scale Parameter K_o = 204 MPa√m

Median K_{Jc} = 188 MPa√m

Reference Temperature T_o = -103 °C

Master Curve· $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 103)]$

Upper Tolerance Bound: K_{Jc} (95%) = $34.5 + 101.3 \exp[0.019 (T + 103)]$

Lower Tolerance Bound: K_{Jc} (5%) = $25.2 + 36.6 \exp[0.019 (T + 86)]$

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = $25.2 + 36.6 \exp[0.019(T + 92)]$

Table 16 - 350WT Weld (W=30 mm) Master Curve Analysis - Quasi-static Loading Rate at -60°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
W350-32	-70	II	10.3	0.3	0.46	96	80
W350-41	-70	III	12.0	0.7	0.45	167	136
W350-40	-70	III	12.0	0.7	0.45	170	139
W350-31	-70	III	12.4	0.7	0.46	181	147
W350-36	-70	III	12.1	0.8	0.45	188	153
W350-37	-70	III	10.4	0.9	0.49	188	153
W350-35	-70	III	12.4	0.8	0.45	194	158
W350-33	-70	III	12.8	1.5	0.46	277	224

Table 17 - 350WT Weld (W=20 mm) - Quasi-static Loading Rate.

Scale Parameter K_o = 153 MPa√m

Median K_{1c} = 141 MPa√m

Reference Temperature T_o = -94 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 94)]$

Upper Tolerance Bound: K_{Jc} (95%) = 34.5 + 101.3 exp[0.019 (T + 94)]

Lower Tolerance Bound: K_{Jc} (5%) = 25.2 + 36.6 exp[0.019 (T + 94)]

Margin Adjusted Lower Bound Curve: : K_{Jc} (LB) = 25.2 + 36.6 exp[0.019(T + 82)]

Table 18 - 350WT Weld (W=20 mm) Master Curve Analysis - Quasi-static Loading Rate at -70°C.

Specimen ID	Temp °C	Type	P_{max} kN	LLD mm	a/W	K_{Jc} MPa√m	K_{Jc} (1T) MPa√m
WF350-6	-50	III	14.9	0.7	0.47	165	-
WF350-9	-50	III	13.9	0.7	0.49	166	-
WF350-15	-60	III	14.3	0.8	0.49	183	-
WF350-25	-70	I	7.3	0.3	0.51	53	46
WF350-21	-70	I	10.6	0.3	0.48	69	59
WF350-23	-70	I	12.5	0.4	0.48	82	69
WF350-18	-70	I	13.0	0.5	0.48	85	72
WF350-20	-70	II	13.7	0.5	0.49	122	102
WF350-26	-70	II	13.7	0.6	0.49	125	104
WF350-27	-70	III	14.4	0.8	0.49	161	132
WF350-16	-70	III	14.6	0.8	0.51	183	149
WF350-17	-80	I	7.7	0.2	0.47	50	-

Table 19 - 350WT Weld - Intermediate Loading Rate.

Scale Parameter K_o = 112 MPa√m

Median K_{Jc} = 104 MPa√m

Reference Temperature T_o = -73 °C

Master Curve: $K_{Jc(median)} = 30 + 70 \exp[0.019(T + 73)]$

Upper Tolerance Bound: $K_{Jc}(95\%) = 34.5 + 101.3 \exp[0.019 (T + 73)]$

Lower Tolerance Bound: $K_{Jc}(5\%) = 25.2 + 36.6 \exp[0.019 (T + 73)]$

Margin Adjusted Lower Bound Curve: : $K_{Jc}(LB) = 25.2 + 36.6 \exp[0.019(T + 61)]$

Table 20 - 350WT Weld Master Curve Analysis - Intermediate Loading Rate at -70°C.

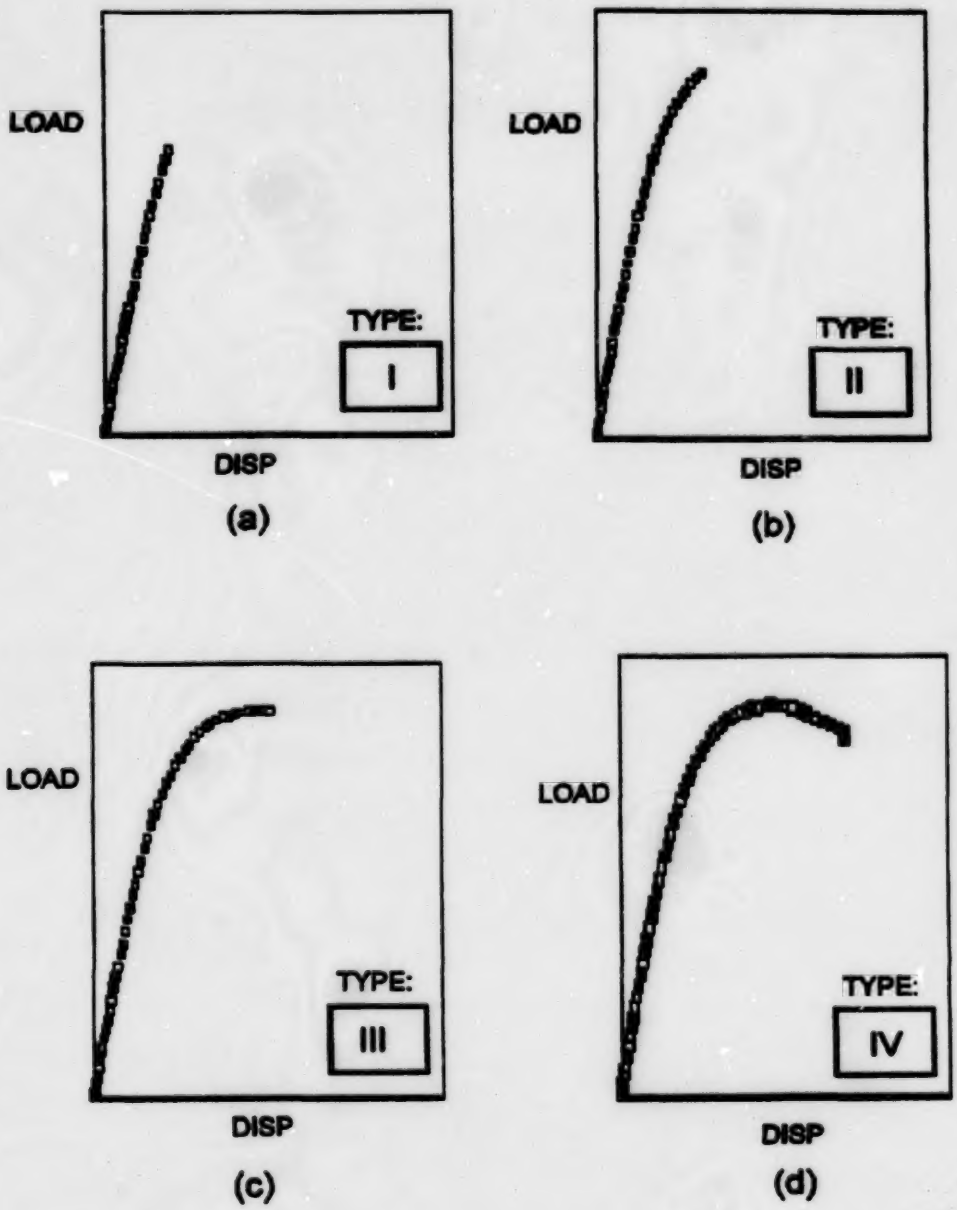


Figure 1 - Material Behaviour Indicated By Load Vs. Displacement Plots: (a) Elastic, (b) Elastic-Plastic Prior To Limit Load, (c) Elastic-Plastic At Limit Load, and (d) Elastic-Plastic Beyond Limit Load.

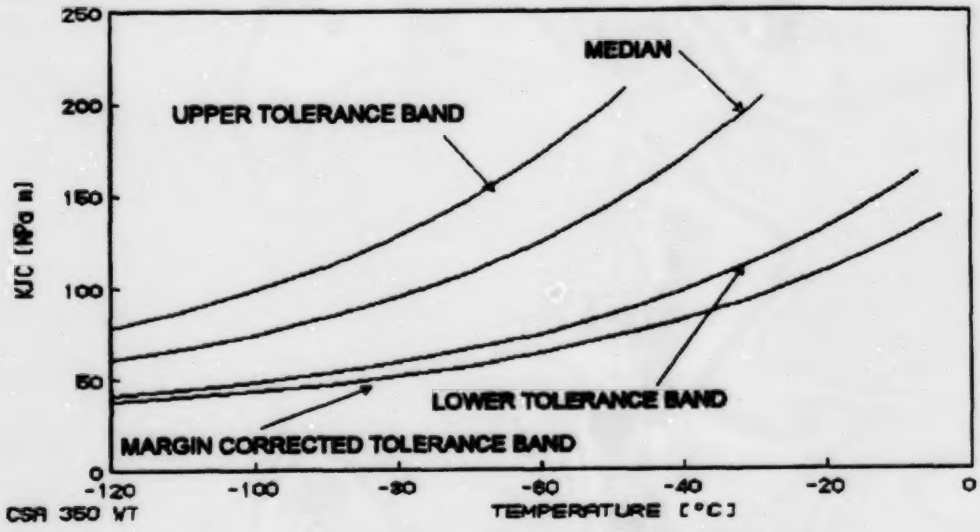


Figure 2 - Typical Master Curve And Tolerance Bands.

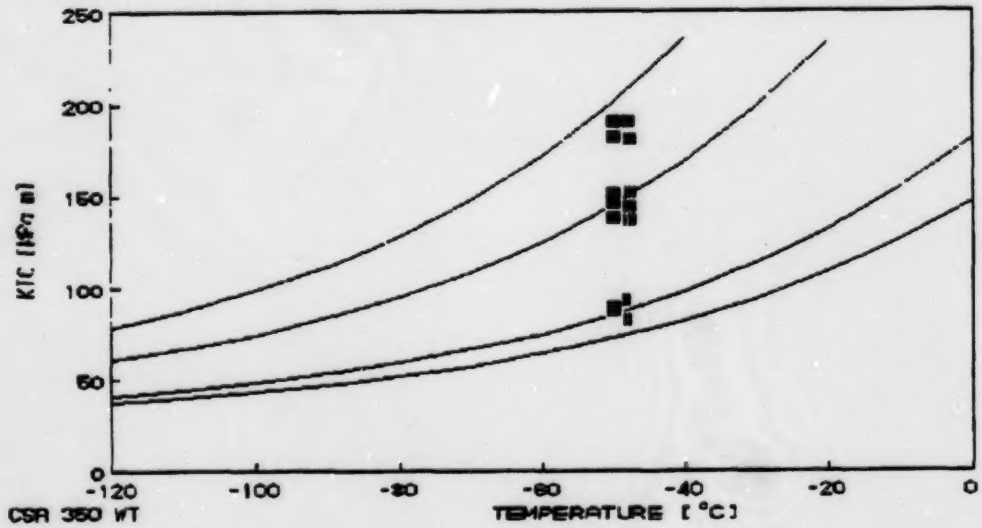


Figure 3 - CSA 350 WT T-L Master Curve. (Quasi-Static Loading At -60°C)

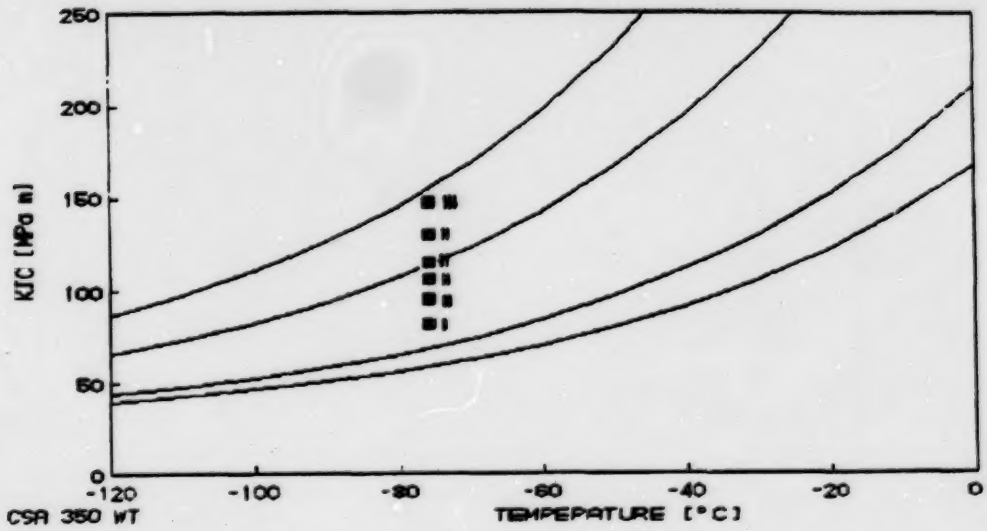


Figure 4 - CSA 350 WT T-L Master Curve.(Quasi-Static Loading at -76°C)

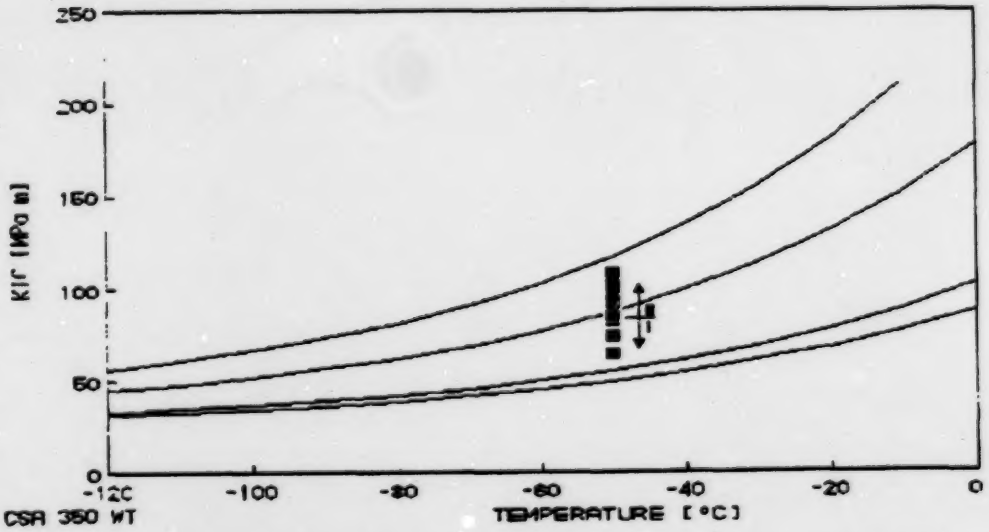


Figure 5 - CSA 350 WT T-L Master Curve. (Intermediate Loading At -60°C)

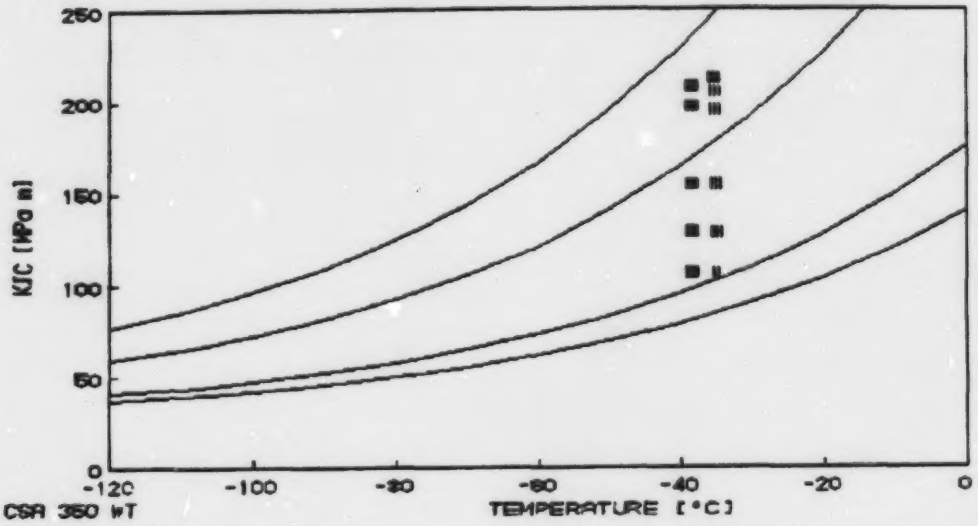


Figure 6 - CSA 350 WT T-L Master Curve (Intermediate Loading At -38°C)

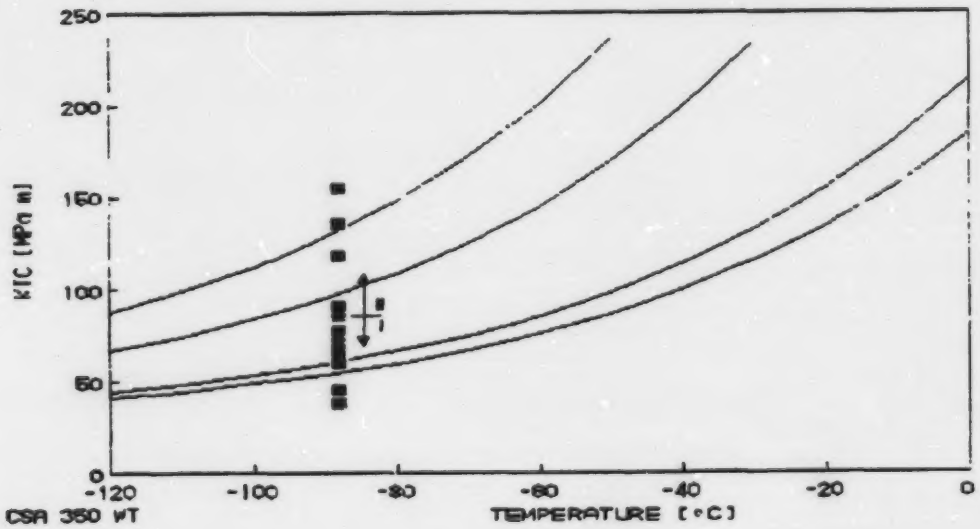


Figure 7 - CSA 350 WT L-T Master Curve. (Intermediate Loading At -88°C)

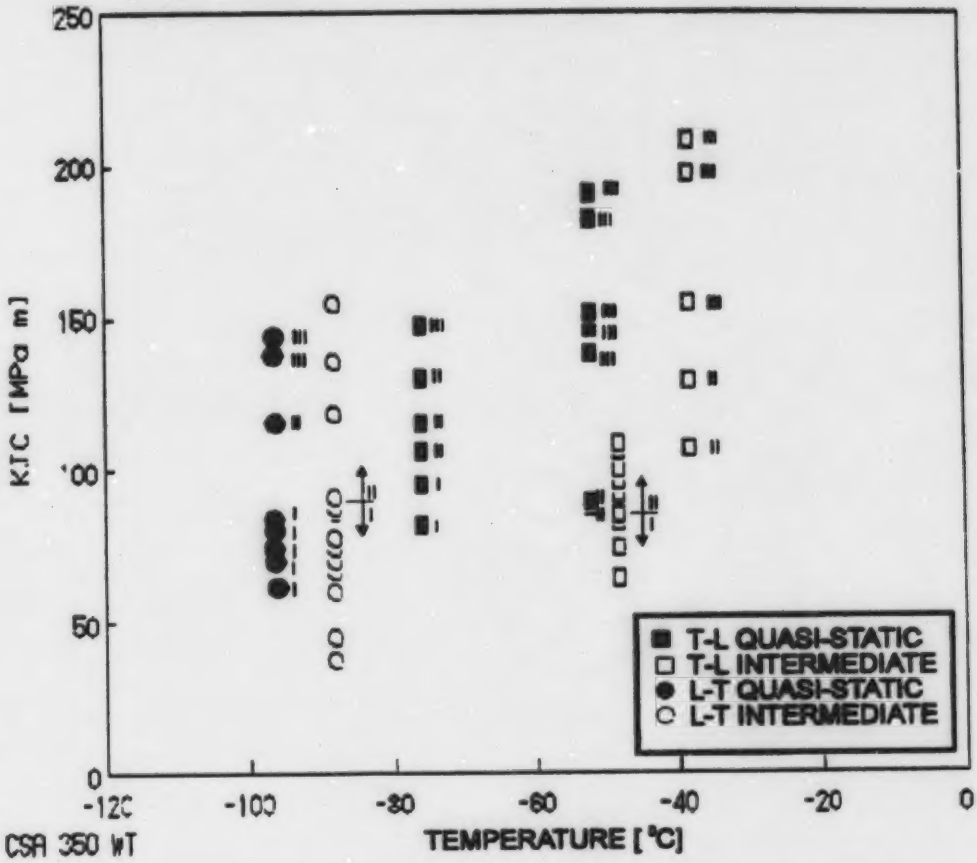


Figure 8 - Combined CSA 350 WT L-T And T-L Results.

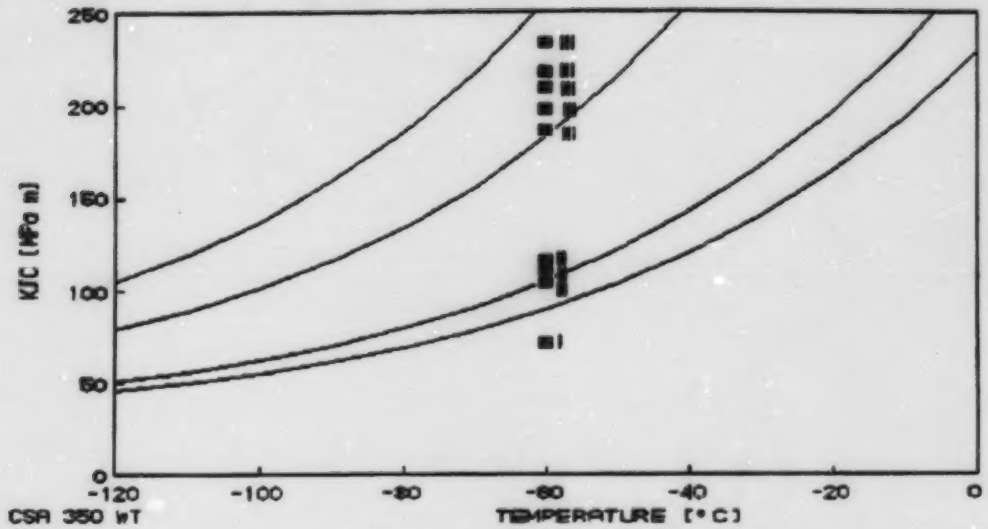


Figure 9 - CSA 350 WT Weld Master Curve. (Quasi-Static Loading at -60°C)

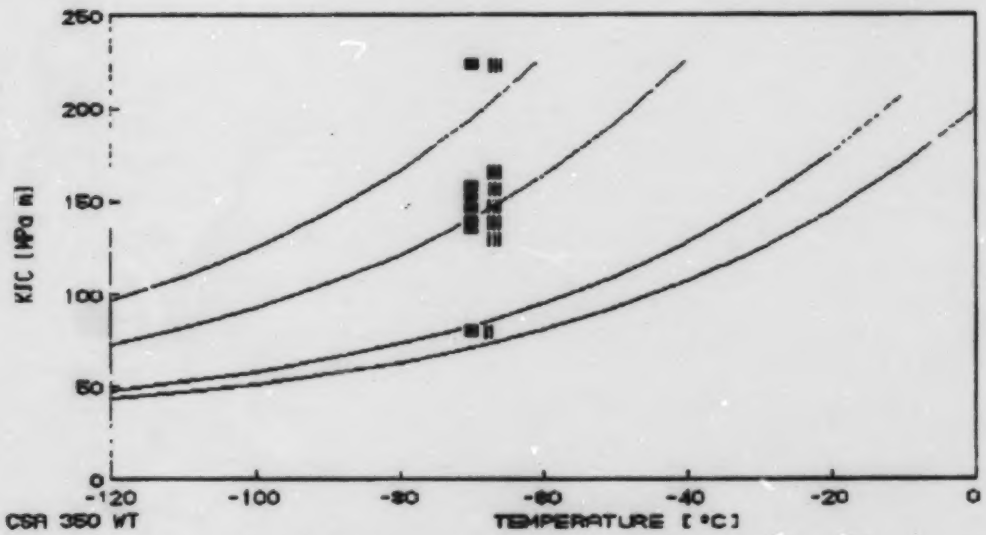


Figure 10 - CSA 350 WT Weld Master Curve. (Quasi-Static Loading At -70°C)

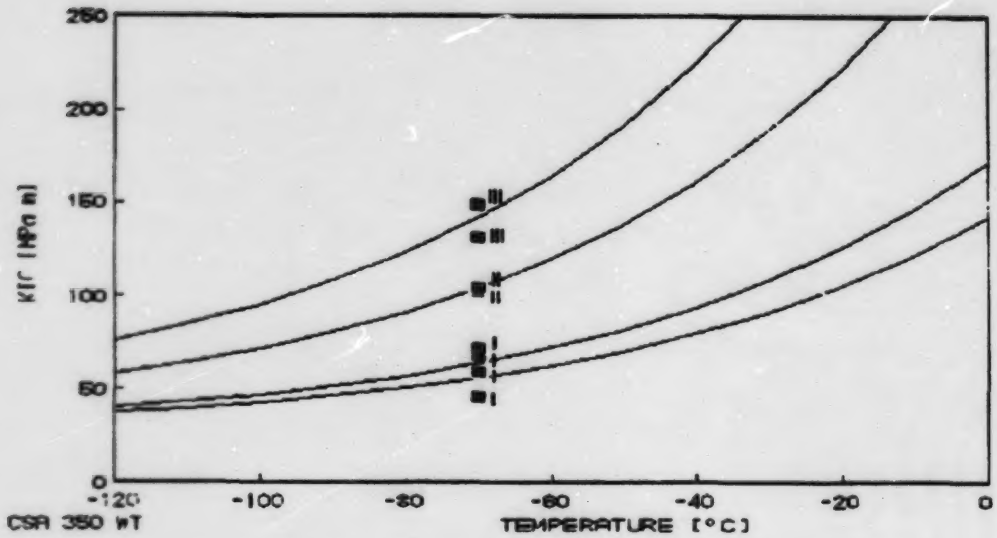


Figure 11 - CSA 350 WT Weld Master Curve. (Intermediate Loading at -70°C)

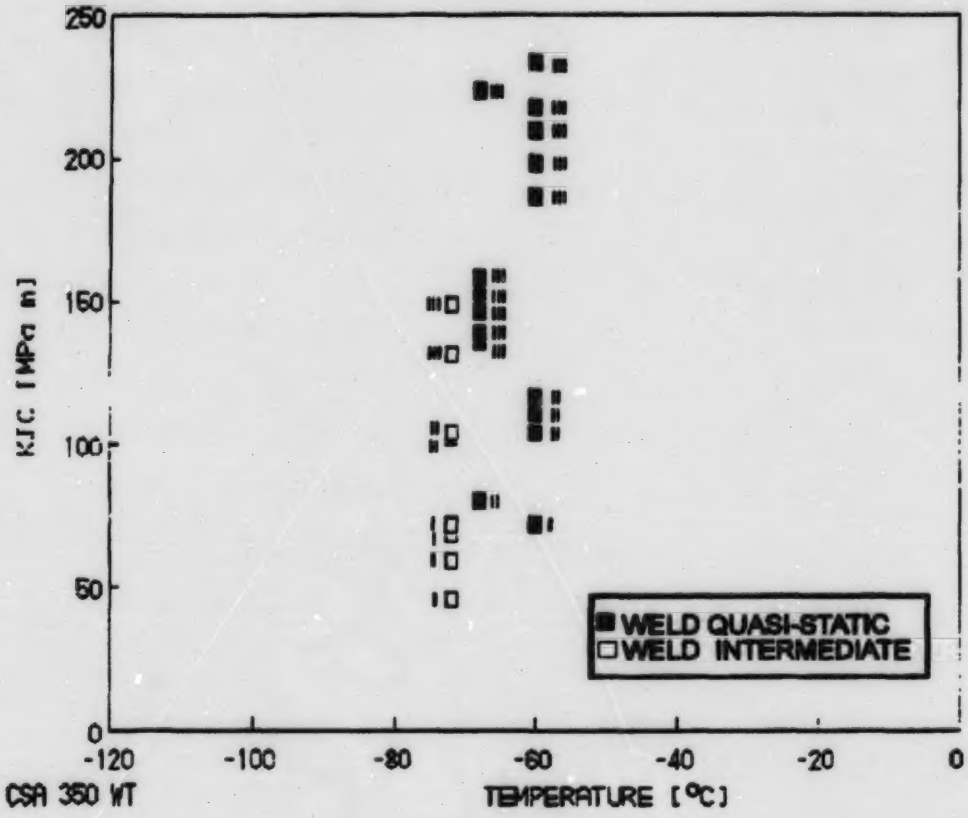
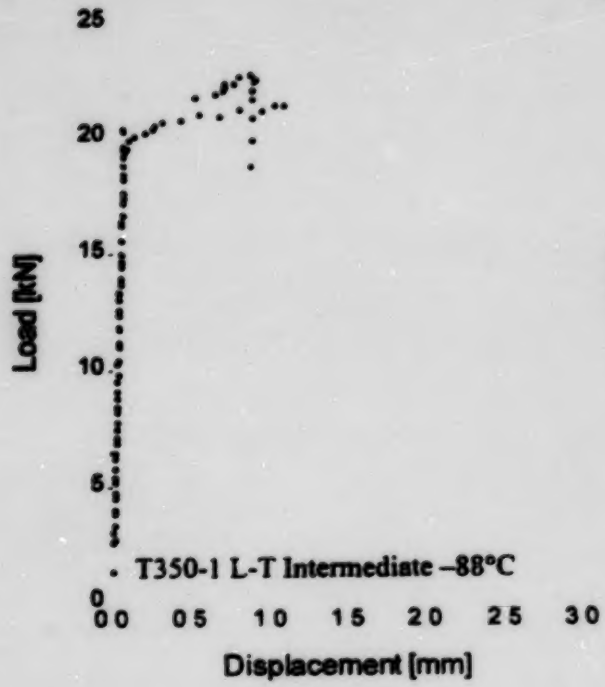
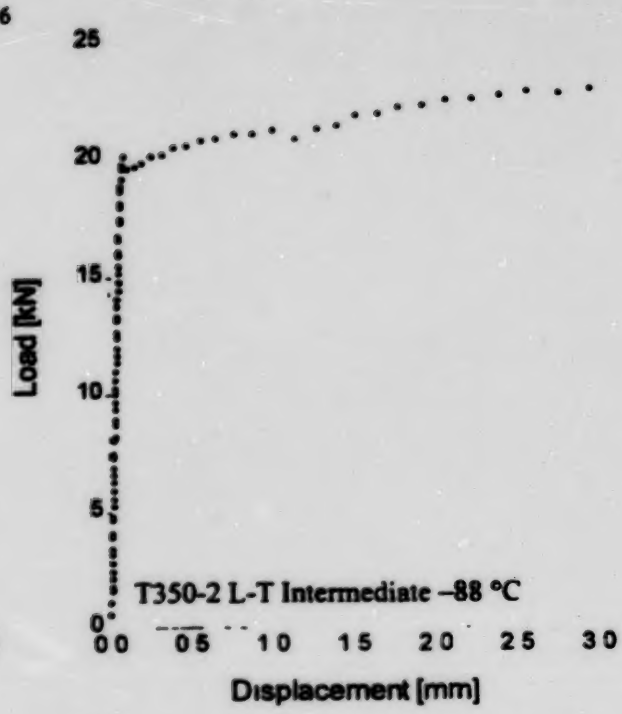


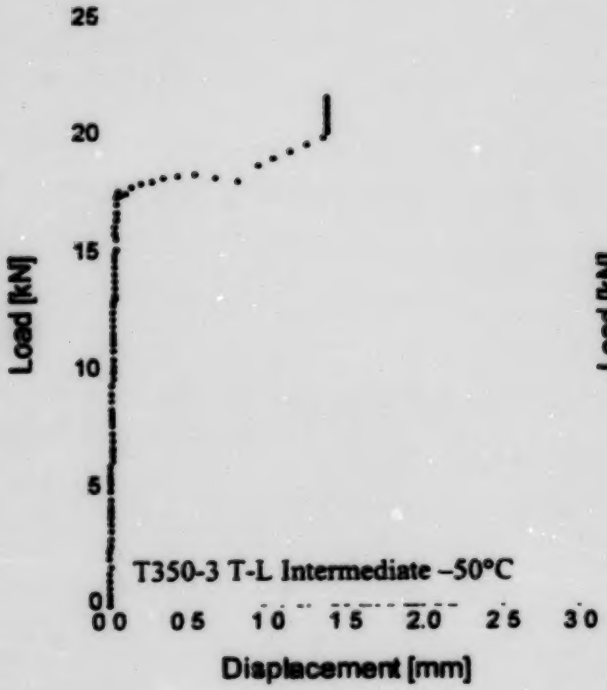
Figure 12 - Combined CSA 350 WT Weld Results.

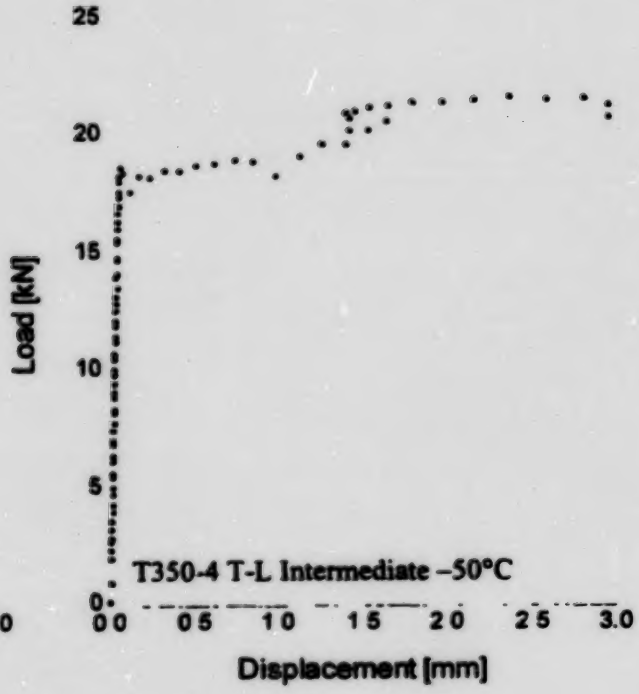
Appendix A

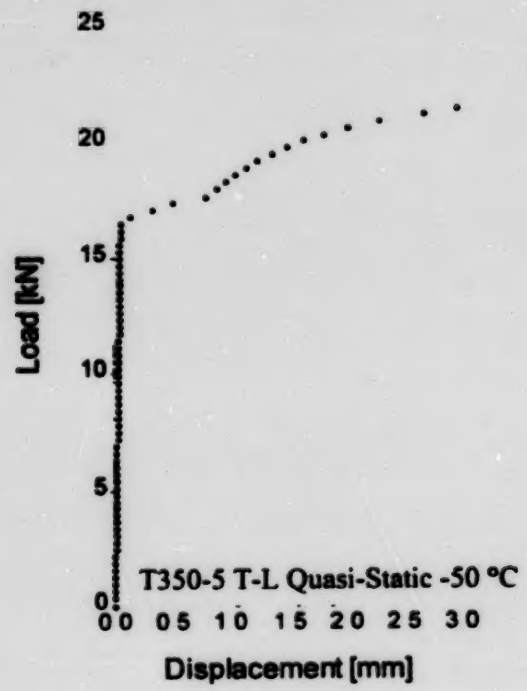
Tensile Test Load-Displacement Curves.

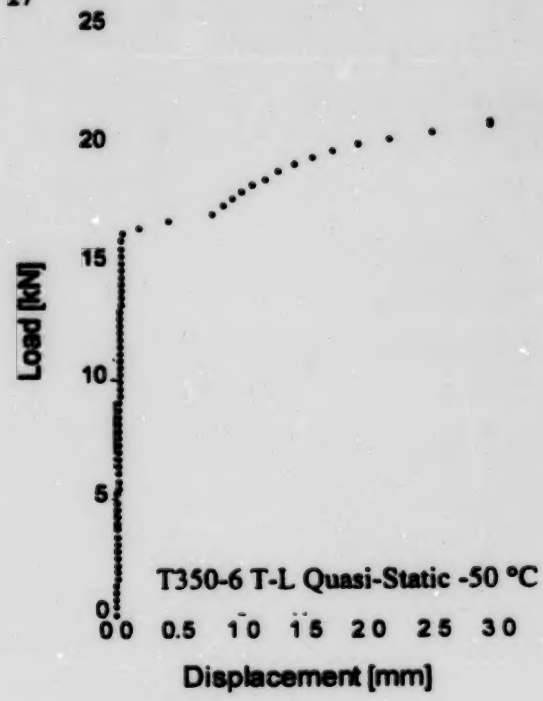

Load [kN]
Displacement [mm]
T350-1 L-T Intermediate –88°C

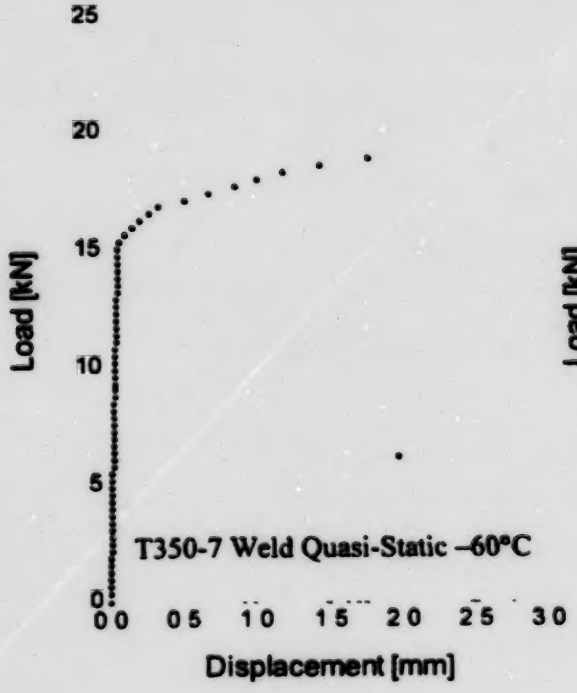

Load [kN]
Displacement [mm]
T350-2 L-T Intermediate –88 °C

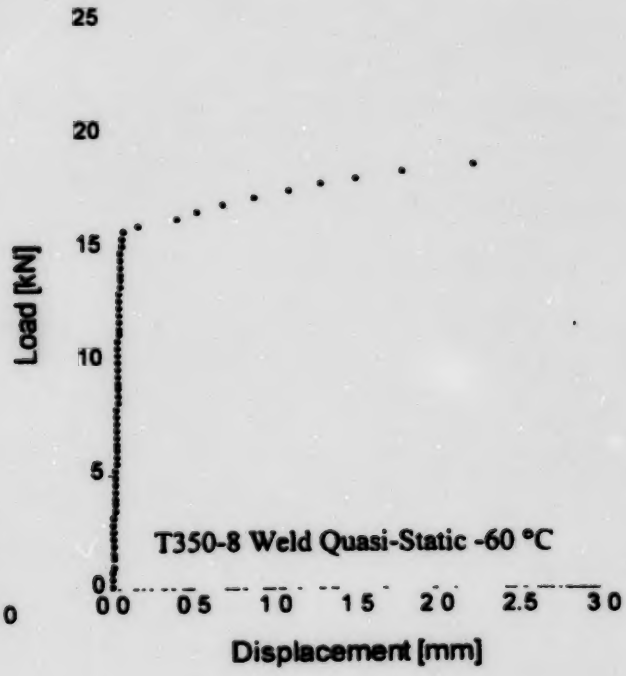

Load [kN]
Displacement [mm]
T350-3 T-L Intermediate –50°C


Load [kN]
Displacement [mm]
T350-4 T-L Intermediate –50°C


Load [kN]
25
20
15
10
5
0
00 05 10 15 20 25 30
Displacement [mm]
T350-5 T-L Quasi-Static -50 °C


Load [kN]
25
20
15
10
5
0
00 0.5 10 15 20 25 30
Displacement [mm]
T350-6 T-L Quasi-Static -50 °C


Load [kN]
25
20
15
10
5
0
00 05 10 15 20 25 30
Displacement [mm]
T350-7 Weld Quasi-Static –60°C


Load [kN]
25
20
15
10
5
0
00 05 10 15 20 2.5 30
Displacement [mm]
T350-8 Weld Quasi-Static -60 °C

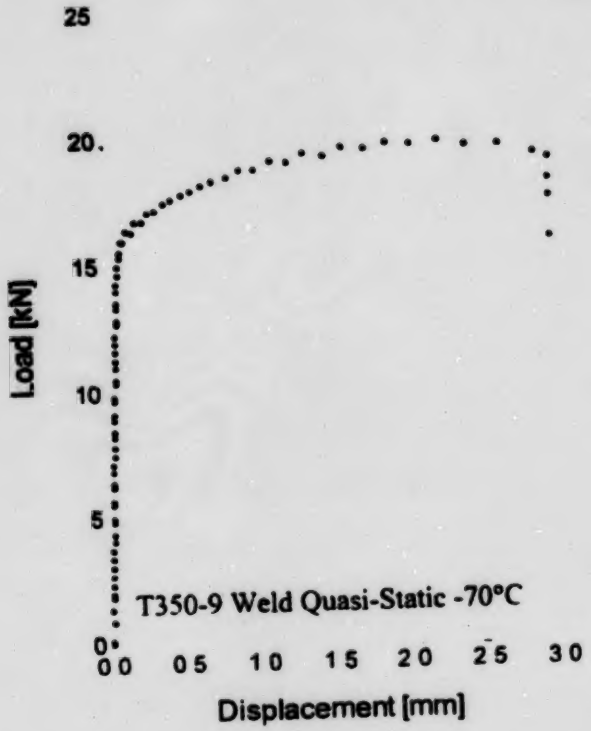


Figure A1 - Tensile Load-Displacement Curves.

Appendix B

Specimen Dimensions, Crack Sizes, and Toughness Measurements

S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave
G350-1	-60	29.78	14.83	11.32	15.90	16.00	16.04	16.02	16.02	15.71	15.69	15.63	15.46	15.84
G350-2	-60	29.80	14.93	11.35	15.72	15.81	15.78	15.82	15.71	15.55	15.42	15.26	15.64	15.64
G350-4	-50	29.81	15 01	11.21	15 10	15.25	15.30	15.35	15.37	15.32	15.25	15.15	15.04	15.26
G350-5	-50	29.82	14.88	11.06	14.94	15.05	15.08	15.11	15.11	15.02	15.03	14.97	14.81	15.03
G350-7	-50	29.76	14 91	11.36	14 97	15.09	15 17	15.13	15.22	15.10	15.12	15.04	14.94	15.10
G350-8	-50	29.82	14.88	11.12	15 11	15.25	15.29	15 33	15.31	15.22	15.15	15.03	14 94	15.20
G350-9	-50	29.80	14.88	11 12	15.12	15.36	15.48	15.59	15.65	15.65	15.61	15.50	15 35	15.51
G350-10	-50	29.76	14.91	11.14	15.35	15.54	15.67	15 75	15.81	15.81	15.82	15.75	15.65	15.71
G350-11	-50	29 78	14 87	10 97	15.17	15.28	15.33	15.35	15.36	15.29	15.21	15 11	14 92	15 25
G350-12	-70	29.80	14 94	11.65	15 14	15.29	15 33	15.32	15 29	15.22	15 15	15 04	14.86	15 20

Table B1 - Specimen Dimensions and Crack Sizes (T-L Quasi-Static (1)).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Ic}/s MPa√m·s
G350-1	-60	0.53	17.8	14.8	95.2	42 4	99 8	142 2	174.4	11 8
G350-2	-60	0.52	15 5	15.0	80 3	30 1	0 0	30.1	80 3	5.4
G350-4	-50	0.51	17 4	12 0	86.2	34.8	10.8	45 6	98 7	8 2
G350-5	-50	0 50	19 0	15 2	93 1	40 5	93 2	133 7	169 1	11.1
G350-7	-50	0 51	17.4	11.1	86 3	34.8	9.3	44.2	97 2	8.8
G350-8	-50	0 51	19 4	15 6	96 3	43.4	68.5	111 9	154 7	9 9
G350-9	-50	0.52	19.2	20.1	98 6	45.4	171.0	216.4	215 2	10.7
G350-10	-50	0 53	18 2	13 6	95.9	43.0	84 8	127.8	165 4	12 2
G350-11	-50	0 51	18 8	17.3	95.3	42.4	153.1	195.5	204.5	11 8
G350-12	-70	0.51	15.2	53.0	73.8	25.5	0 0	25.5	73.8	1.4

Table B2 - Fracture Toughness Results (T-L Quasi-Static(1)).

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S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave.
350X-1	-76	29.96	15.02	11.88	14.82	15.05	15.13	15.23	15.22	15.19	15.16	15.05	14.90	15.11
350X-2	-76	29.98	15.02	11.63	14.91	15.21	15.30	15.41	15.44	15.45	15.44	15.38	15.19	15.33
350X-3	-76	29.98	15.03	11.88	15.24	15.51	15.60	15.66	15.68	15.70	15.68	15.61	15 48	15.60
350X-4	-76	29.96	15.00	11.34	15.25	15.48	15.57	15.66	15.69	15 71	15.71	15 66	15.52	15.61
350X-5	-76	29.96	15 05	11 41	15.04	15.28	15.38	15 44	15.48	15.48	15.44	15.36	15.28	15.38
350X-6	-76	29 96	15 02	11 61	14.87	15 04	15 11	15.14	15.13	15.09	15.07	14.99	14 79	15.05

Table B3 - Specimen Dimensions and Crack Sizes (T-L Quasi-Static(2)).

S/N	T °C	a/W	P_m kN	t_f s	K_c MPa√m	J_e	J_p kJ/m^2	J_c	K_{Jc} MPa√m	K_{Jc}'s MPa√m/s
350X-1	-76	0 50	15 8	5.6	74.2	25.7	13.3	39.0	91.3	16.3
350X-2	-76	0 51	18 3	21.8	88.6	36.7	27.6	64.3	117.3	5.4
350X-3	-76	0.52	18 5	14.4	90 9	38.6	37.4	76.0	127.5	8.9
350X-4	-76	0.52	19 1	17.8	96 7	43.7	84.9	128.6	165 9	9.3
350X-5	-76	0 51	17 9	9.5	86 3	34.8	16.9	51 7	105.2	11.1
350X-6	-76	0.50	20 4	11.9	95.9	43 0	56.6	99 7	146.0	12.3

Table B4 - Fracture Toughness Results (T-L Quasi-Static(2)).

S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave.
G350-13	-50	29.78	14.90	11.05	15.29	15.50	15.68	15.64	15.68	15.66	15.62	15.56	15.51	15.59
G350-15	-50	29.78	14.92	11.05	14.63	14.70	14.77	14.83	14.81	14.78	14.79	14.76	14.66	14.76
G350-16	-50	29 78	14.72	11.13	15.09	15.27	15.36	15.38	15.40	15.40	15.32	15.32	15.19	15.32
G350-17	-50	29 78	14.94	11.03	15 44	15.62	15.74	15.82	15.89	15.91	15.92	15.88	15.81	15.80
G350-18	-50	29.78	14.97	11.49	15.97	16.05	16.07	16.10	16.06	15.98	15.88	15.76	15.58	15.96
G350-19	-50	29.78	14.94	11.12	15.33	15.49	15.61	15.71	15.78	15.78	15.78	15.76	15.69	15.68
G350-20	-50	29.78	14.94	10.66	14.87	15.01	15 11	15.19	15.22	15.24	15 29	15 25	15 17	15 17
G350-22	-50	29 78	14.76	10.64	15.62	15.72	15 77	15.80	15.76	15 71	15.63	15.52	15.32	15.67
G350-23	-50	29 78	14 86	11.30	15.57	15.67	15 70	15 72	15 70	15 67	15 61	15.49	15.33	15 63
G350-24	-50	29 78	14.89	11.19	16 05	16 23	16 32	16 40	16 38	16 37	16 36	16.27	16 10	16 30

Table B5 - Specimen Dimensions and Crack Sizes (T-L Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
G350-13	-50	0.52	18.4	0.33	96 4	43 5	14.6	58.1	111.4	337 0
G350-15	-50	0 50	19 4	0 35	92 8	40 2	8 4	48.6	102 0	291 4
G350-16	-50	0 51	17.9	0 33	90 1	38 0	3.6	41.6	94.3	285.8
G350-17	-50	0.53	18 3	0.40	97.7	44.6	23.3	67 9	120 6	301.5
G350-18	-50	0.54	16.9	0.23	89.8	37.7	1.8	39.5	91 9	399.6
G350-19	-50	0.53	18.2	0 23	95 7	42.8	21.8	64.6	117.6	511.3
G350-20	-50	0.51	13.7	0.20	69.5	22.6	0.0	22.6	69.5	347.5
G350-22	-50	0.53	18.3	0.23	97.8	44.7	8.7	53.4	106 9	464 8
G350-23	-50	0.52	15.6	0.18	81.0	30 7	0.	30.7	81 0	450.0
G350-24	-50	0 55	14 6	0.18	82.0	31.5	0 0	31.5	82.0	455.6

Table B6 - Fracture Toughness Results (T-L Intermediate).

S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave.
350X-7	-38	29.98	15.00	11.72	15.03	15.21	15.29	15.29	15.28	15.26	15.19	15.07	14.92	15.20
350X-8	-38	29.98	15.02	11.66	15.39	15.56	15.62	15.62	15.57	15.53	15.49	15.38	15.20	15.50
350X-9	-38	29.98	15.02	11.54	15.22	15.41	15.47	15.53	15.59	15.59	15.55	15.48	15.32	15.48
350X-10	-38	29.96	14.99	11.45	15.02	15.27	15.33	15.37	15.37	15.31	15.23	15.15	15.01	15.26
350TL16	-38	29 98	15 00	11 83	14 98	15.20	15.27	15.30	15.31	15.29	15.26	15.15	15.01	15.22
350TL17	-38	29.96	15 04	11.81	15 08	15 33	15.39	15.43	15.37	15 44	15.39	15.27	15.09	15.34

Table B7 - Specimen Dimensions and Crack Sizes (T-L Intermediate(2)).

S/N	T °C	a/W	P_m kN	t_f s	K_c MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
350X-7	-38	0.51	20.0	0 25	94.9	42 1	55.4	97.5	144 4	576.6
350X-8	-38	0.52	18.4	0 20	90.5	38.2	27.5	65.7	118.6	593.0
350X-9	-38	0.52	20 0	0 37	98 6	45.4	211.1	256 5	234 2	632 9
350X-10	-38	0.51	20 3	0.39	98 5	45.3	185 7	231 0	222.3	570 0
350TL16	-38	0.51	21 1	0 29	99 9	46.7	208.6	255 3	233.7	805 8
350TL17	-38	0.51	20.3	0.38	97.5	44.4	96.6	141 1	173.7	457 1

Table B8 - Fracture Toughness Results (T-L Intermediate(2)).

S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave
F350-1	-88	30.0	14.86	11.53	14.9	15.12	15.30	15.44	15.49	15.47	15.42	15.32	15.14	15.32
F350-2	-88	30.01	14.95	11.52	15.24	15.41	15.50	15.55	15.51	15.39	15.27	15.12	14.89	15.35
F350-3	-88	29 99	14.90	11.07	15.66	15.82	15.93	15 99	15.97	15.87	15.76	15.62	15.47	15.82
F350-4	-88	29.94	14.92	11.12	15.23	15.42	15.52	15.56	15.62	15.62	15.56	15.43	15.23	15.50
F350-5	-88	29.96	14.93	11.05	15.17	15.38	15.52	15.62	15.66	15.61	15.52	15.36	15.14	15.48
F350-6	-88	30.00	14.96	11.86	15.01	15.24	15.38	15.43	15.44	15.36	15.22	15.07	14.86	15.26
F350-8	-88	29.98	14.92	11.49	15.36	15.57	15.68	15.75	15.74	15.64	15.57	15.46	15.23	15.88
F350-9	-88	30.00	14.92	11.58	15.98	16.13	16.15	16.16	16.21	16.24	16.16	15.99	15.73	16.11
F350-11	-88	29.98	14.93	11.41	15.38	15.56	15.64	15.78	15.86	15.82	15.75	15.61	15.41	15.68
F350-12	-88	29 98	14 98	11.53	15 51	15.66	15.73	15.74	15.74	15.75	15.70	15 58	15.42	15.67
F350-13	-88	30.00	15.02	11.81	15.64	15 76	15.84	15.85	15.83	15 82	15 78	15.70	15.56	15 77
F350-14	-88	30 00	15.04	11 75	14.31	14 45	14.54	14 64	14.70	14.68	14.61	14 54	14.36	14 69
F350-15	-88	30 00	15 04	11 95	14 11	14.25	14 25	14 05	13.95	14 09	14 19	14.15	14 07	14 13
F350-16	-88	29 98	15 05	11 91	15 03	15.19	15.20	15 03	14.80	14.95	15.10	15.16	15.09	15 06
F350-17	-88	29 98	15.06	12.00	15.29	15 43	15.51	15.55	15.59	15 48	15.40	15.26	15 14	15.43

Table B9 - Specimen Dimensions and Crack Sizes (L-T Intermediate).

S/N	T °C	a/W	P_m kN	t_f s	K_c MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
F350-1	-88	0 51	13 5	0.15	65 5	20.0	0.0	20 0	57 5	383.3
F350-2	-88	0.51	11.5	0 18	65 4	19.9	14.3	34 3	85.7	476 1
F350-3	-88	0.53	19.4	0.38	101 6	48 3	0.0	48 3	101.6	267 4
F350-4	-88	0 52	14 6	0.25	74.0	25.6	0 0	25.6	74.0	296 0
F350-5	-88	0.52	22.2	0.50	112 3	58 9	23.0	81 9	132 4	264 8
F350-6	-88	0 51	19 5	12 3	92 3	39.8	2 9	42.7	95.6	7 77
F350-8	-88	0 53	19.2	0 23	96.2	43.3	0.0	43.3	88.5	384 8
F350-9	-88	0 54	9 2	0.13	48.4	11.0	0 0	11.0	48.4	372.3
F350-11	-88	0.52	22.3	0.33	113.0	59 7	48.5	108.2	152 2	461.2
F350-12	-88	0.52	8 0	0 13	40.3	7.5	0 0	7 5	40.3	310.0
F350-13	-88	0.53	13.0	0 12	65 0	19 8	7.9	27.7	77.0	641 7
F350-14	-88	0 49	17 3	0 27	77 2	27.9	3.4	31.3	81.8	302.9
F350-15	-88	0.47	25.8	0.47	108 1	54 6	86.1	140.7	173.5	369 1
F350-16	-88	0 50	19 1	0 33	88 5	36.6	6.6	43.2	96.1	291.2
F350-17	-88	0.51	17.5	0 31	84 0	33.0	9.1	42.1	94.9	306.1

Table B10 - Fracture Toughness Results (L-T Intermediate).

S/N	T °C	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave.
							mm							
W350-2	-40	29.98	10.41	7.49	15.01	14.98	14.52	14.56	14.61	14.68	14.84	14.91	14.90	14.76
W350-10	-50	29.98	9.89	6 98	15.55	15.54	15.50	15.46	15.40	15.50	15.67	15.85	16.10	15.59
W350-8	-60	30.00	10.03	7.48	14.73	14.40	14.26	14.31	14.41	14.62	14.88	14.94	15.14	14.59
W350-11	-60	29.98	10 0	7.47	15.58	15.40	15.30	15.12	14.98	14.92	14.97	14.98	14.96	15.12
W350-12	-60	29.96	9 97	7.09	14.56	14.56	14.49	14.46	14.44	14.54	14.63	14.67	14.75	14.56
W350-13	-60	29 96	9.88	7.30	16.27	16.14	16.00	15.93	15.90	15.91	15.91	15.88	15.85	15.97
W350-14	-60	29.98	9.96	7 27	16 81	16 82	16.83	16.79	16.79	16.73	16.68	16.63	16.39	16.73
W350-19	-60	29 98	9.96	7 10	15 98	16.11	16.21	16.28	16.32	16.45	16.53	16.67	16.76	16.37
W350-22	-60	30.00	9.96	7.38	14.91	14.89	14.78	14.67	14.59	14.55	14.63	14 74	14.87	14.72
W350-24	-60	29.98	10.01	7.74	14.84	14.79	14 60	14.52	14.60	14.47	14.90	15.13	15.23	14.76
W350-42	-60	30.00	9.91	7.63	14.23	14.08	13.87	13.74	13.76	13.87	13 98	13.88	13.65	13.89
W350-43	-60	30.00	9.89	7.84	14.43	14.18	13.99	13.89	13.83	13 99	14.06	14.38	14.43	14.09
W350-44	-60	30.00	10.02	7 89	15 79	15.81	15.80	15.82	15.76	15 69	15.66	15.47	15 04	15.68

Table B11 - Specimen Dimensions and Crack Sizes (Weld 30mm Quasi-Static).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
W350-2	-40	0 49	13 0	20 9	88 4	36.5	40 2	76 7	128 2	6.1
W350-10	-50	0.49	11 2	14 4	76.5	27 3	7 4	34 8	86 2	6 0
W350-8	-60	0 52	12 9	28 8	102.0	48 6	238.6	287.2	247.9	8.6
W350-11	-60	0 50	12 3	22 2	88.8	36.8	47 9	84.8	134 7	6.1
W350-12	-60	0 49	13 7	29.2	96.2	43.2	237.8	281.0	245 2	8.4
W350-13	-60	0.53	12 9	44 4	103.3	49 9	339.8	389.8	288.8	6 5
W350-14	-60	0.56	10 9	25 5	95 9	43.0	115.1	158.1	183 9	7.2
W350-19	-60	0.55	12 0	29.2	102 2	48.8	344.3	393.1	290 0	9.9
W350-22	-60	0.49	14 1	29.6	97.8	44 7	200.4	245.1	229.0	7.7
W350-24	-60	0.49	12.4	19.3	84.3	33.2	41.3	74 5	126 3	6.5
W350-42	-60	0.46	15 0	35 4	94.6	41 9	300.3	342.2	270 6	7.7
W350-43	-60	0.47	14 8	27.1	94 1	41.4	275 2	316.6	260.3	9.6
W350-44	-60	0.52	12.0	9.0	89.3	37.3	56.5	93.8	141.6	15.7

Table B12 - Fracture Toughness Results (Weld 30mm Quasi-Static).

S/N	T °C	W	B	B_N	a_1	a_2	a_3 mm	a_4	a_5	a_6	a_7	a_8	a_9	ave.
W350-32	-70	20.5	10.02	7.98	9.61	9.71	9.58	9.45	9.39	9.34	9.45	9.56	9.73	9.52
W350-31	-70	20.5	10.02	8.01	9.6	9.38	9.23	9.22	9.25	9.34	9.52	9.64	9.63	9.40
W350-33	-70	20 5	9 93	7.77	9.39	9.39	9.33	9.27	9.29	9.34	9.37	9.43	9.57	9.36
W350-35	-70	20.5	9.99	8.18	9.54	9.53	9.32	9.01	8.91	9.20	9.42	9.48	9.45	9 30
W350-36	-70	20.5	9.95	8.09	9.63	9.60	9.38	9.19	9.09	9.04	9.11	9.17	9.36	9.26
W350-37	-70	20.5	9.96	8 10	10.11	10 17	10.13	10.09	10.10	10.08	10.07	10.15	10.19	10 12
W350-40	-70	20.52	9 99	8 04	9 20	9.21	9 09	9.07	9.14	9.27	9.30	9 37	9.36	9.22
W350-41	-70	20 48	9 97	7.96	9 26	9.27	9.21	9.13	9.07	9 08	9.16	9.18	9.28	9 17

Table B13 - Specimen Dimensions and Crack Sizes (Weld 20mm Quasi-Static).

S/N	T °C	a/W	P_m kN	t_f s	K_e MPa√m	J_e	J_p kJ/m²	J_t	K_{Jc} MPa√m	K_J/s MPa√m/s
W350-31	-70	0 46	12.4	19.7	88.4	36.5	115.8	152.3	180.5	9.1
W350-32	-70	0.46	10 3	21.0	74.5	25.9	17.4	43.3	96.3	4 6
W350-33	-70	0 46	12 8	72.3	92 5	40.0	317.5	357 4	276 5	3.8
W350-35	-70	0 45	12 4	22 6	86 6	35.0	140.7	175 7	193 9	8 8
W350-36	-70	0 45	12 1	30.8	84 4	33.2	132.7	166.0	188 4	6 1
W350-37	-70	0.49	10.4	32.9	82.3	31.7	133.8	165.5	188.2	5 7
W350-40	-70	0 45	12.0	21.8	83.3	32.4	102.0	134.4	169 6	7 8
W350-41	-70	0 45	12.0	18.5	83.2	32.4	97.7	130 0	166.8	9 0

Table B14 - Fracture Toughness Results (Weld 20 mm Quasi-Static).

S/N	T °C	W	B	B_N	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	ave.
							mm							
WF350-6	-50	29.98	9.97	7.60	14.86	14.43	14.15	14.06	14.05	14.14	14.19	14.24	14.27	14.23
WF350-9	-50	29.98	9 98	7.67	14.82	14.83	14.77	14.72	14.66	14 67	14.67	14.80	14.92	14.75
WF350-15	-70	29.98	9.97	7.53	14.82	14.78	14.74	14.65	14.61	14.58	14.62	14.71	14.79	14.69
WF350-16	-70	29.97	10 00	7.72	15.29	15.38	15.30	15.20	15.11	15.05	14.98	15.05	15.07	15.16
WF350-17	-70	30.00	10.03	7.60	14.47	14.49	14.38	14.25	14.00	13.97	14.03	14.23	14.43	14.23
WF350-18	-70	29 98	10.02	7.82	14.65	14.63	14.53	14.44	14.35	14.32	14.31	14.38	14.47	14.44
WF350-20	-70	30.00	9.99	7.63	14.88	14.81	14.69	14.67	14.72	14.81	14.86	14.99	14.87	14.80
WF350-21	-70	29.96	10.02	7.80	14.67	14.45	14.36	14.28	14.23	14.29	14.37	14.52	14.54	14.39
WF350-23	-70	29.96	10.02	7 65	14.76	14.68	14.47	14.35	14 15	14.04	14.05	14.19	14.39	14.31
WF350-25	-70	30 00	9 99	7.88	15 34	15 36	15.41	15.39	15.39	15.42	15.48	15.59	15.62	15.44
WF350-26	-70	30.00	10.04	7.74	15.05	14.91	14.72	14.73	14.68	14.72	14 71	14.73	14.69	14.76
WF350-27	-70	29.96	9.99	7 17	14 42	14 38	14.32	14.36	14 51	14 71	14.90	15 05	15.05	14.62

Table B15 - Specimen Dimensions and Crack Length Measurements (Weld Intermediate).

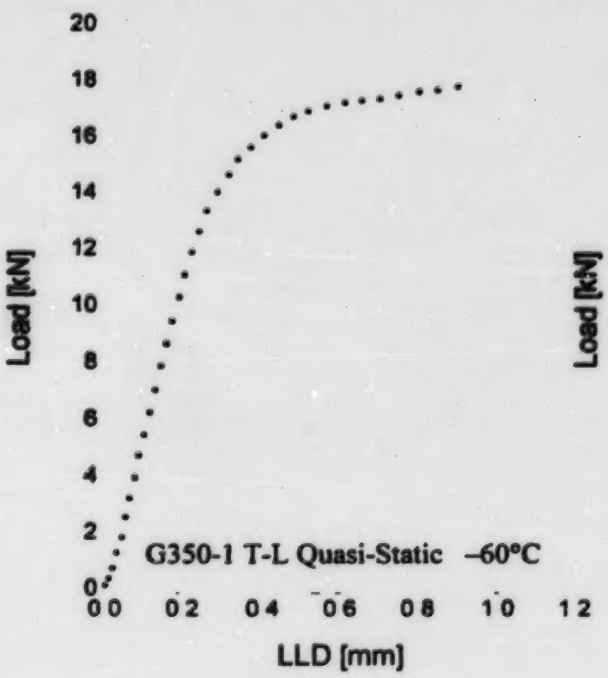
S/N	T °C	a/W	P_m kN	t_f s	K_c MPa√m	J_e	J_p kJ/m²	J_c	K_{Jc} MPa√m	K_{Jc}/s MPa√m/s
WF350-6	-50	0 47	14 9	0.19	10 0	46.9	79 5	126 3	164 4	865.3
WF350-9	-50	0.49	13.9	0 16	95.3	42.5	87.5	130.0	166.7	1.041 9
WF350-15	-70	0.49	14 3	0.23	98 4	45.2	112.3	157 5	183.6	798 3
WF350-16	-70	0.51	14.6	0.18	107.1	53.6	103.2	156.9	183.2	1,017 8
WF350-17	-70	0.51	7.7	0 06	50.0	11.7	0.0	11 7	50 0	833 3
WF350-18	-70	0 48	13.0	0 15	85.4	34.0	0.0	34.0	85 4	569 3
WF350-20	-70	0.49	13 7	0.20	94.5	41 7	28.6	70.3	122.7	613.5
WF350-21	-70	0.48	10.6	0.11	69.5	22 5	0.0	22.5	69.5	631.8
WF350-23	-70	0.48	12.5	0 14	82.1	31.5	0.0	31.5	82.1	586.4
WF350-25	-70	0 51	7.3	0 06	53.0	13.1	0.0	13.1	53 0	883 3
WF350-26	-70	0 49	13.7	0 16	93.2	40.6	32.7	73.3	125.2	782.5
WF350-27	-70	0 49	14.4	0 20	101.1	47.8	73.6	121.4	161 1	805 5

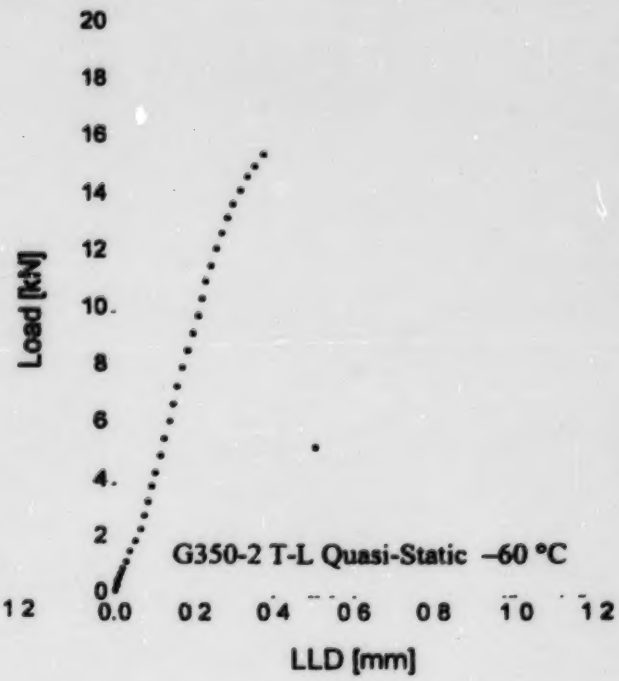
Table B16 - Fracture Toughness Results (Weld Intermediate).

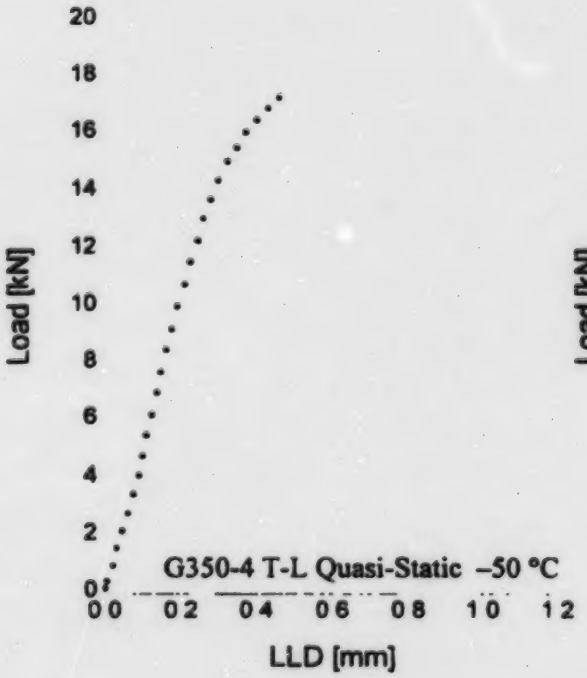
Appendix C

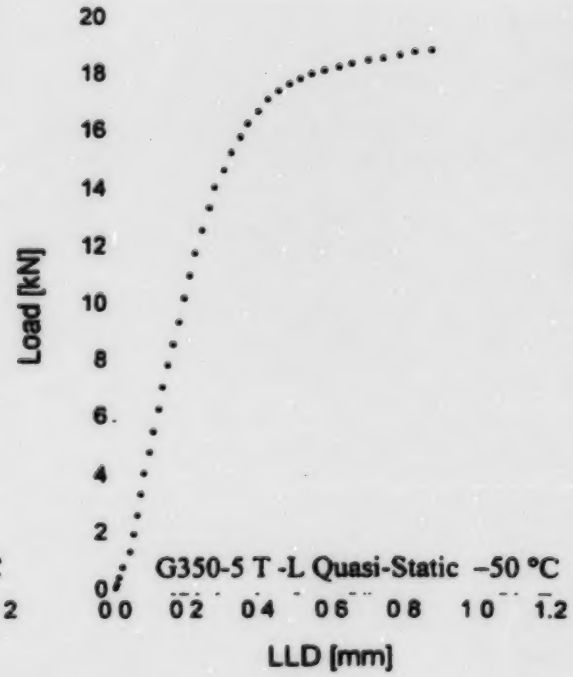
K_{Jc} Load-Load Line Displacement Curves

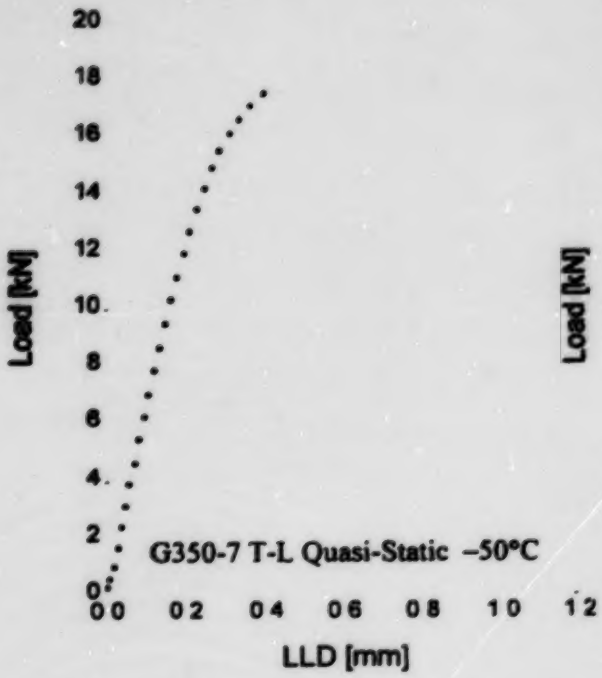
350WT Plate
T-L Orientation
Quasi-Static Loading Rate

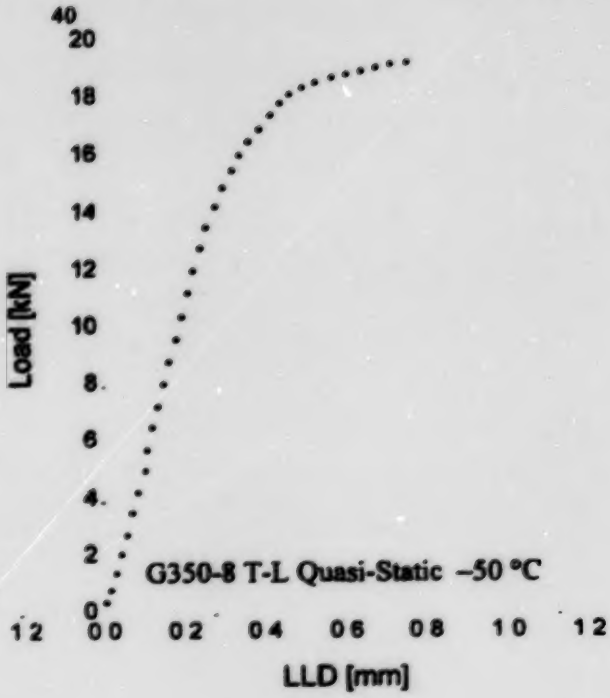

Load [kN]
LLD [mm]
G350-1 T-L Quasi-Static –60°C

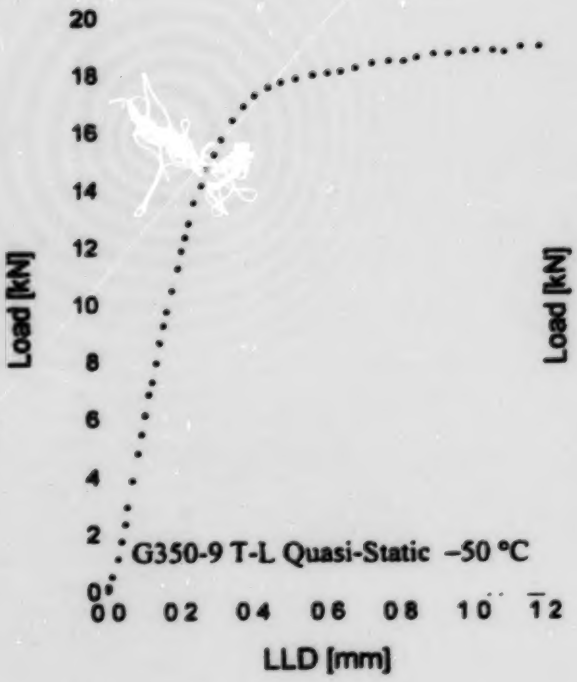

Load [kN]
LLD [mm]
G350-2 T-L Quasi-Static –60 °C

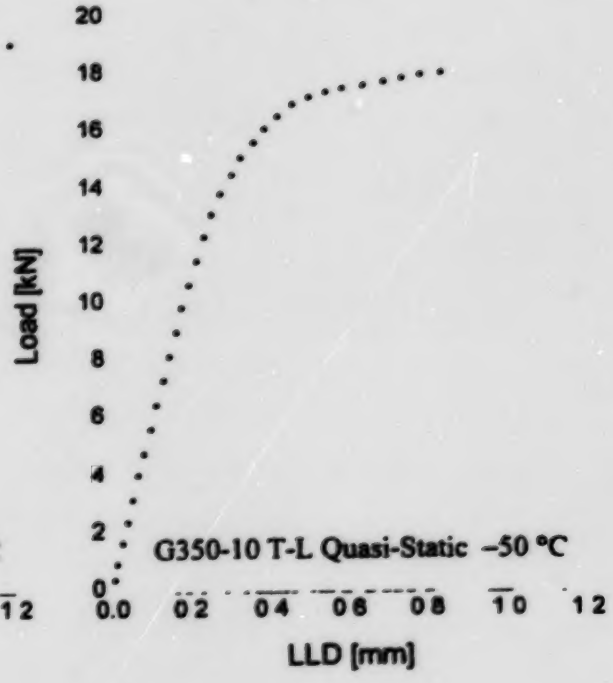

Load [kN]
LLD [mm]
G350-4 T-L Quasi-Static –50 °C

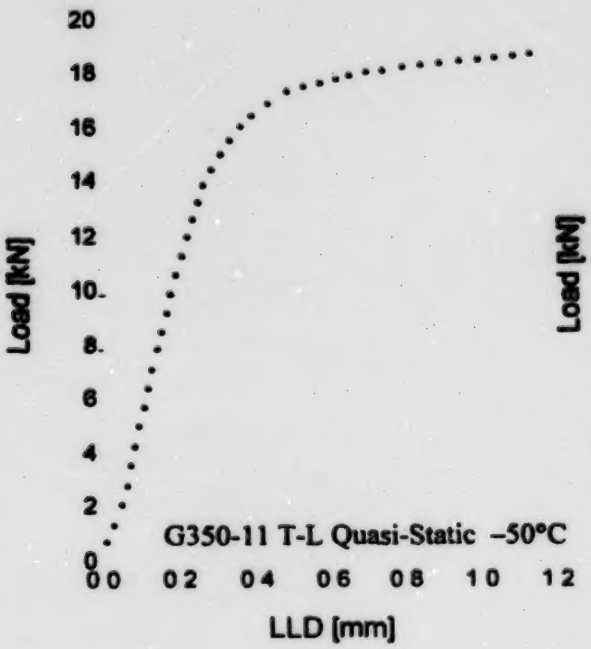

Load [kN]
LLD [mm]
G350-5 T -L Quasi-Static –50 °C

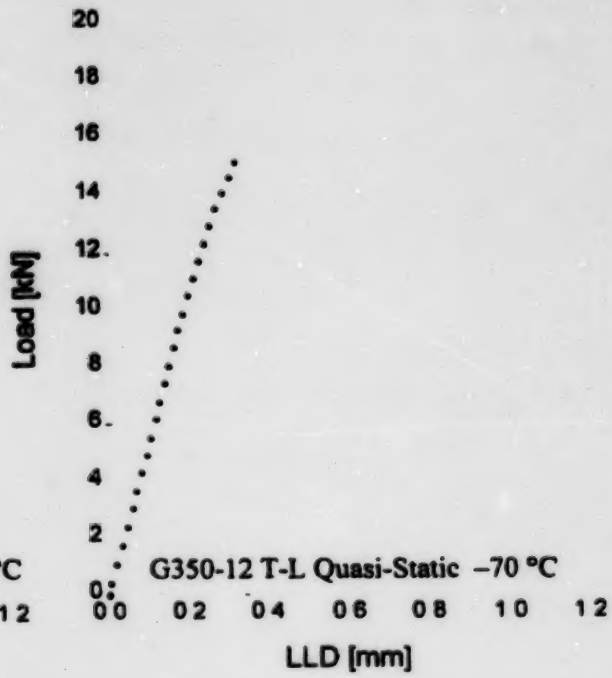

Load [kN]
LLD [mm]
G350-7 T-L Quasi-Static –50°C

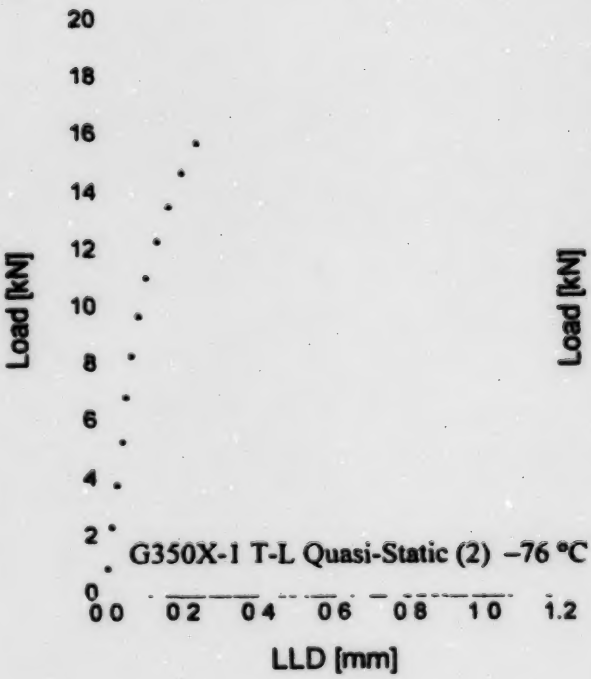

Load [kN]
LLD [mm]
G350-8 T-L Quasi-Static –50 °C

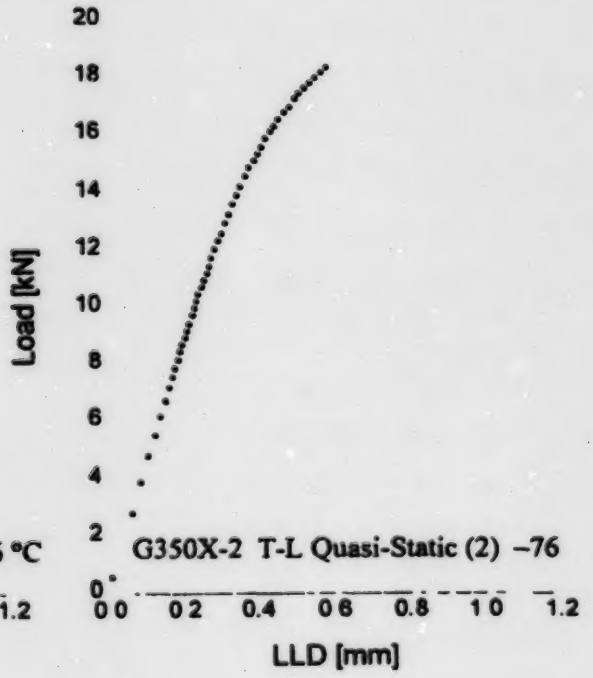

Load [kN]
LLD [mm]
G350-9 T-L Quasi-Static –50 °C

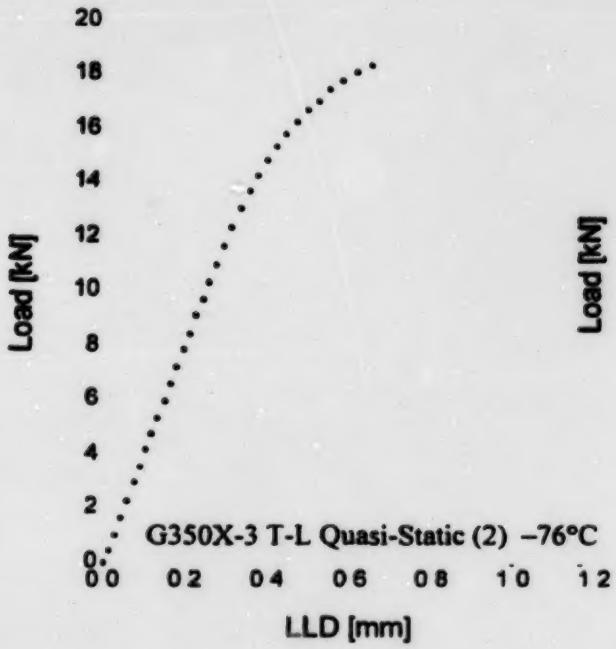

Load [kN]
LLD [mm]
G350-10 T-L Quasi-Static –50 °C

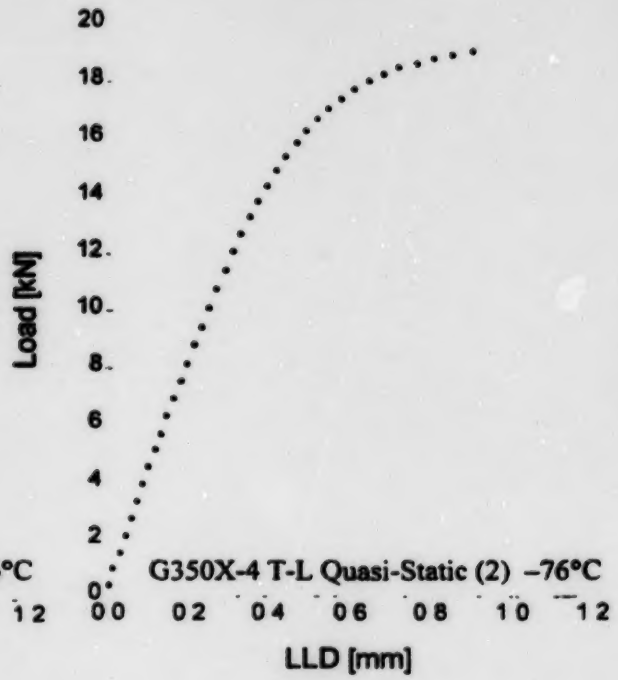

Load [kN]
LLD [mm]
G350-11 T-L Quasi-Static –50°C

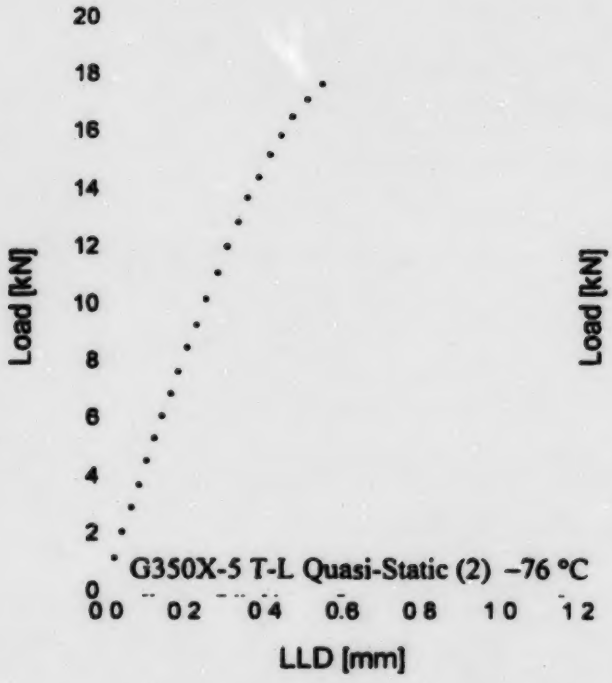

Load [kN]
LLD [mm]
G350-12 T-L Quasi-Static –70 °C

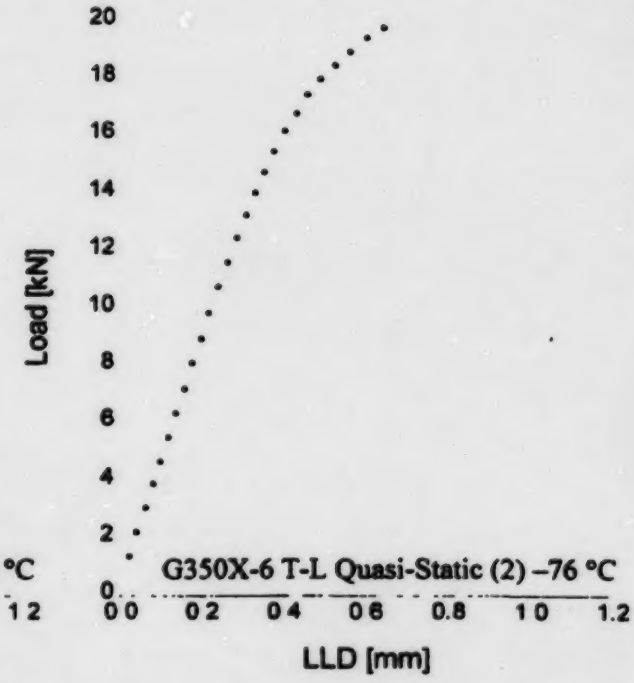

Load [kN]
LLD [mm]
G350X-1 T-L Quasi-Static (2) –76 °C


Load [kN]
LLD [mm]
G350X-2 T-L Quasi-Static (2) –76


Load [kN]
LLD [mm]
G350X-3 T-L Quasi-Static (2) –76°C


Load [kN]
LLD [mm]
G350X-4 T-L Quasi-Static (2) –76°C

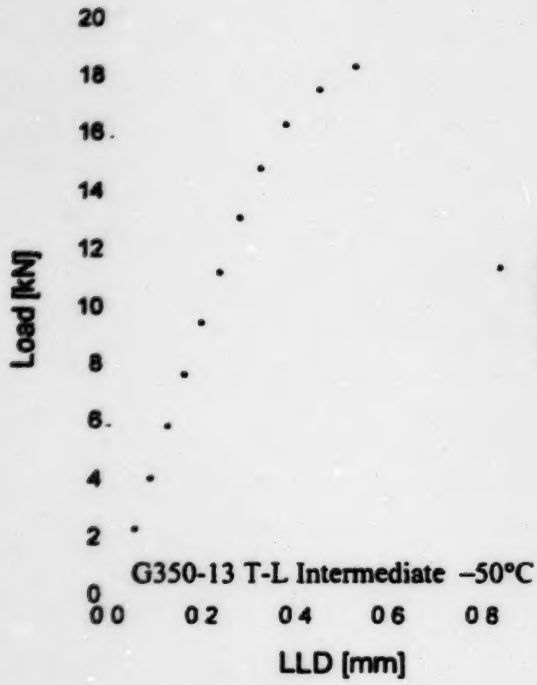

Load [kN]
LLD [mm]
G350X-5 T-L Quasi-Static (2) –76 °C

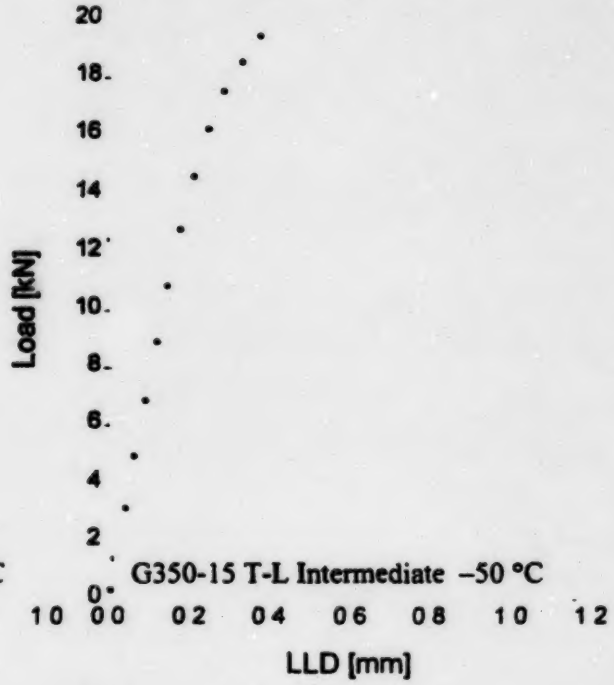

Load [kN]
LLD [mm]
G350X-6 T-L Quasi-Static (2) –76 °C

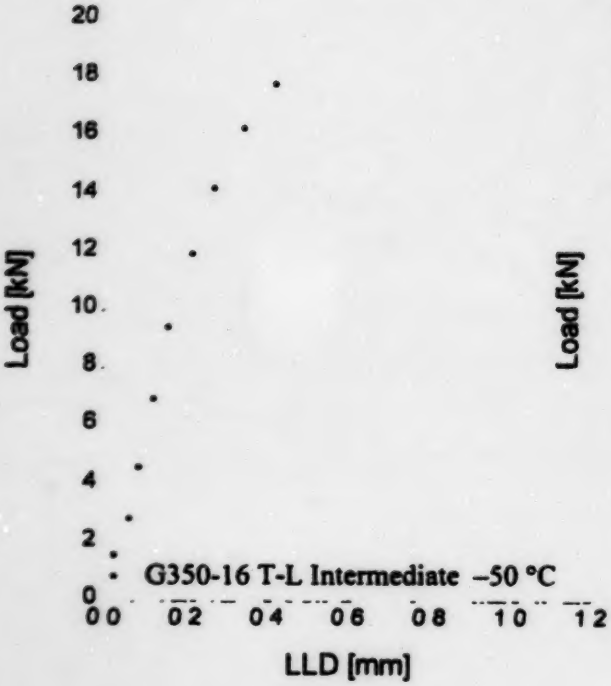
Appendix D

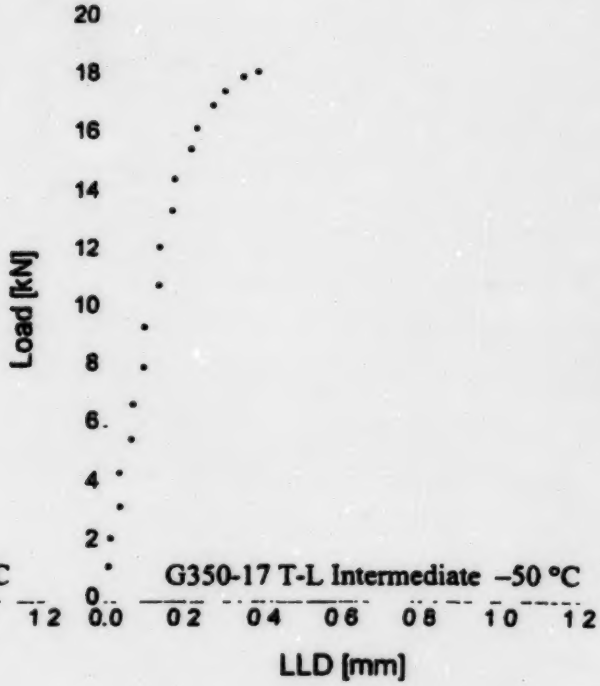
K_{Jc} Load-Load Line Displacement Curves

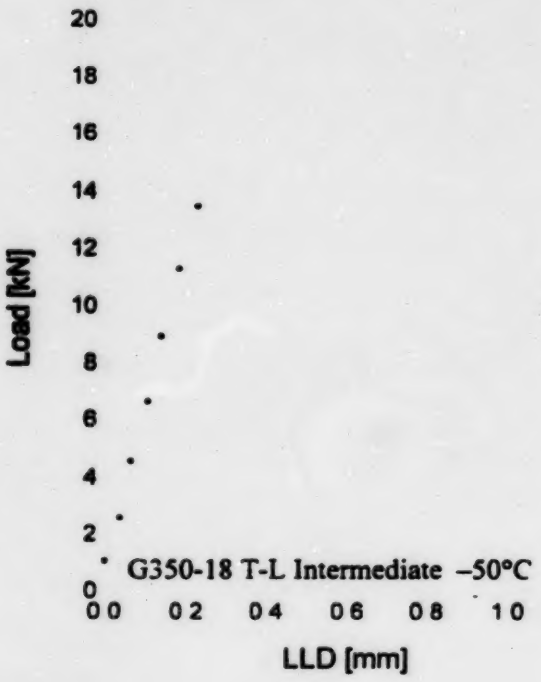
350WT Plate
T-L Orientation
Intermediate Loading Rate

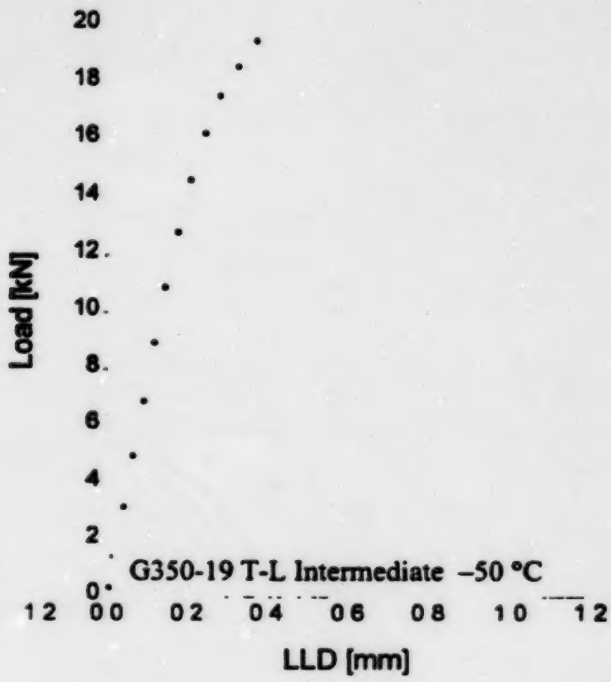

Load [kN]
LLD [mm]
G350-13 T-L Intermediate –50°C

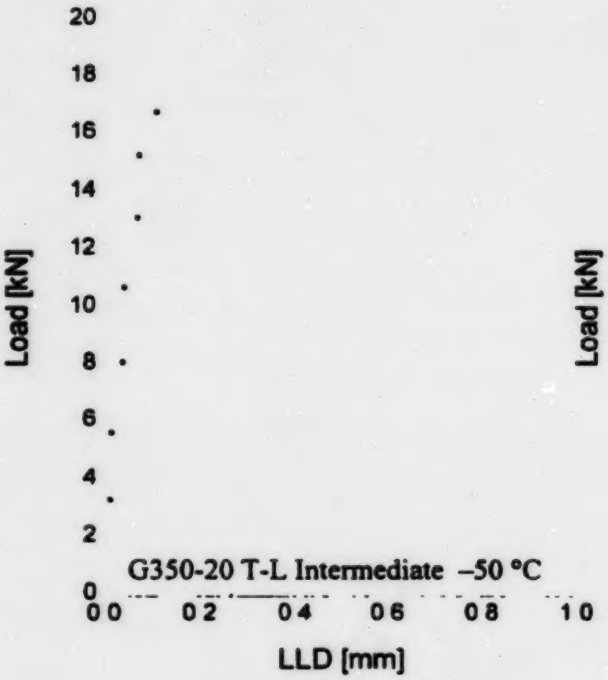

Load [kN]
LLD [mm]
G350-15 T-L Intermediate –50 °C

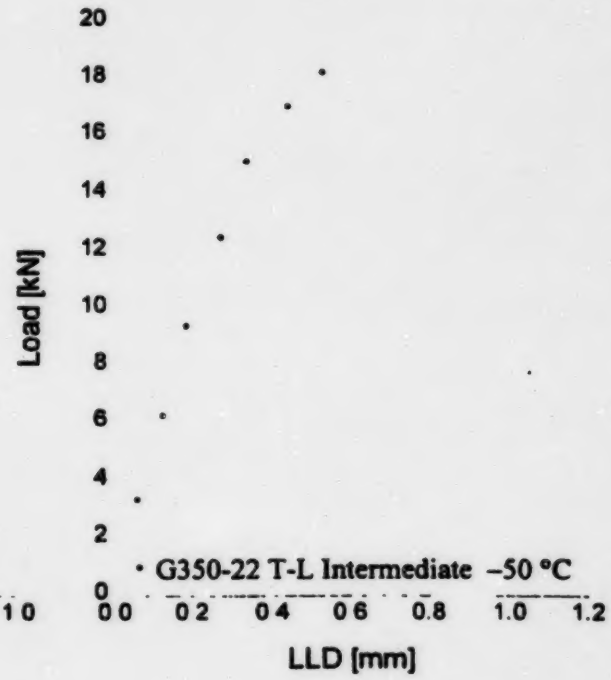

Load [kN]
LLD [mm]
G350-16 T-L Intermediate –50 °C

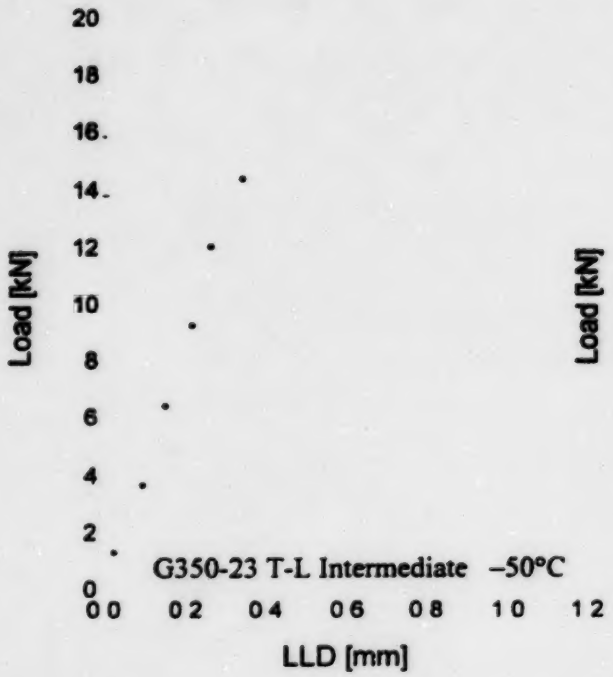

Load [kN]
LLD [mm]
G350-17 T-L Intermediate –50 °C

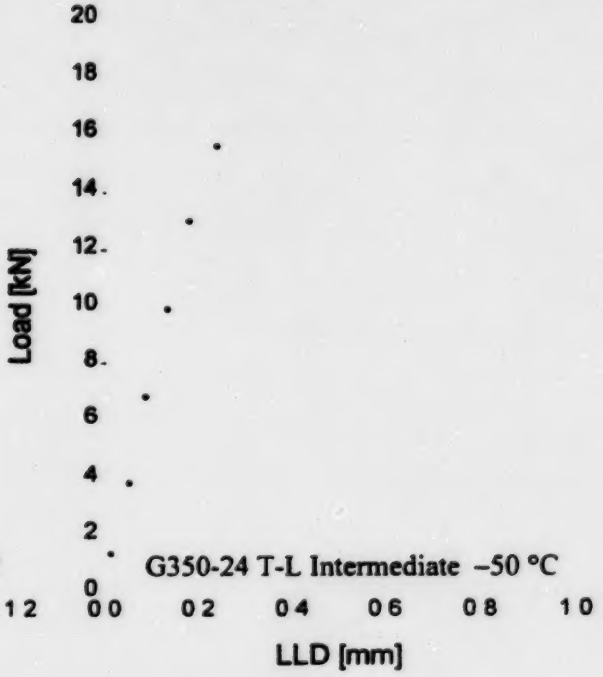

Load [kN]
LLD [mm]
G350-18 T-L Intermediate –50°C

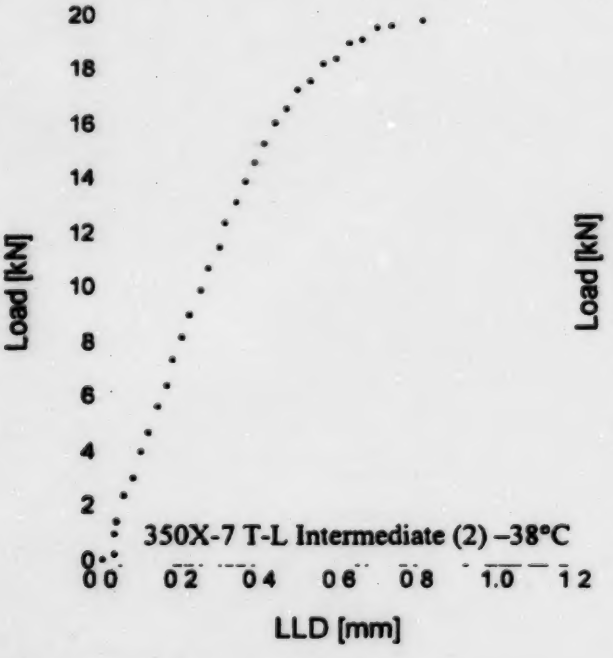

Load [kN]
LLD [mm]
G350-19 T-L Intermediate –50 °C

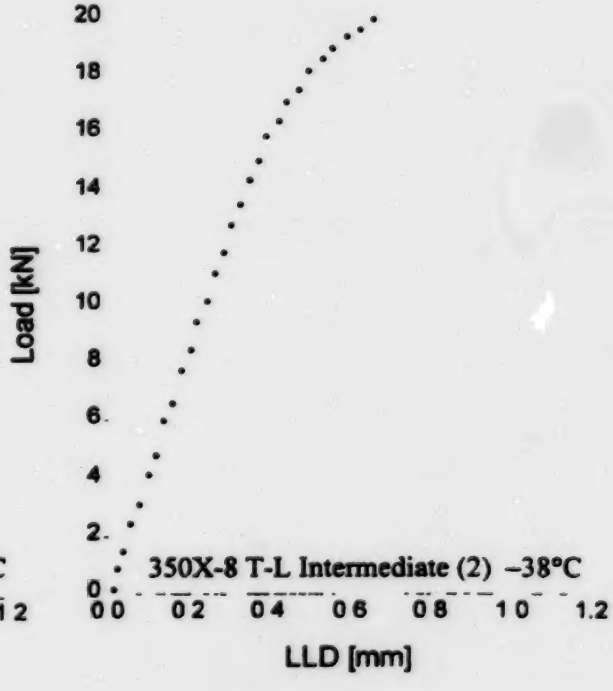

Load [kN]
LLD [mm]
G350-20 T-L Intermediate –50 °C

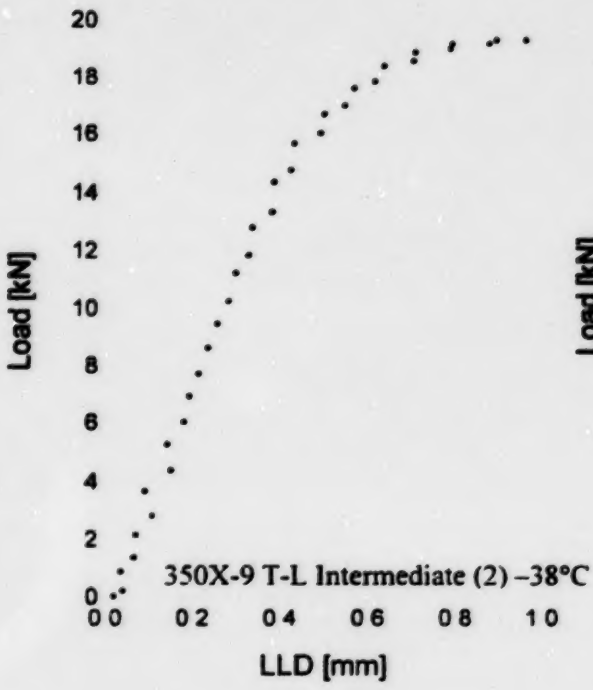

Load [kN]
LLD [mm]
G350-22 T-L Intermediate –50 °C

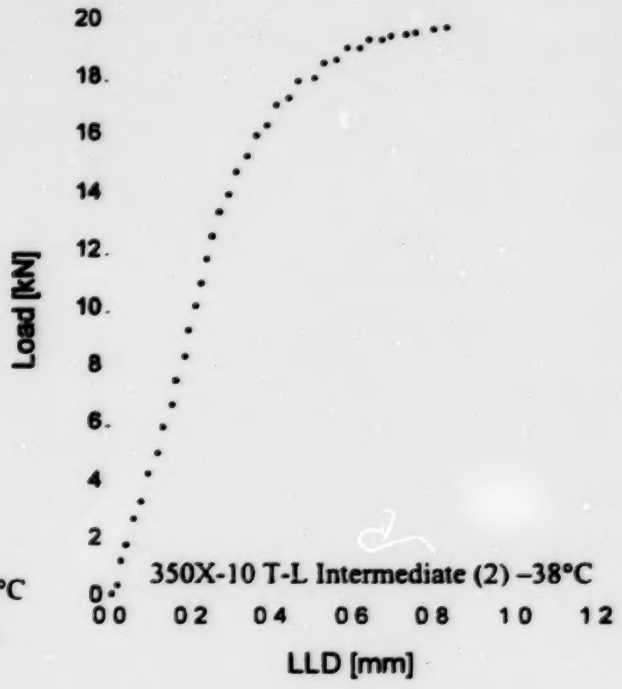

Load [kN]
LLD [mm]
G350-23 T-L Intermediate –50°C

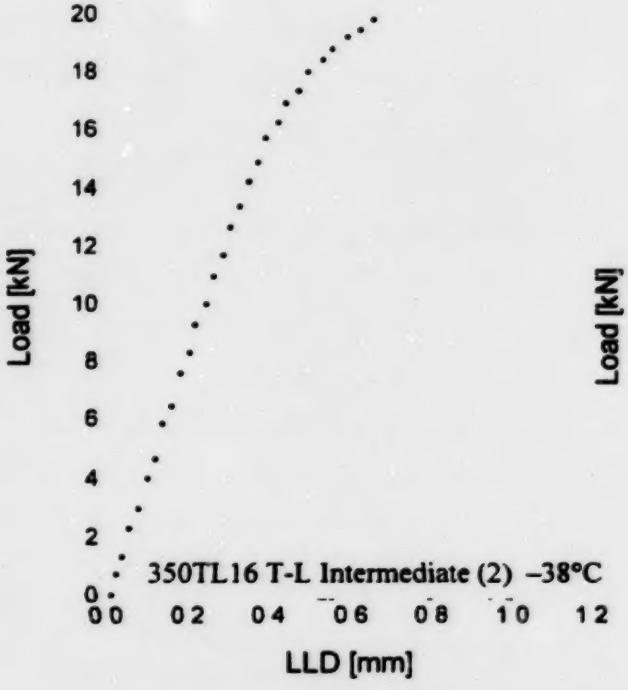

Load [kN]
LLD [mm]
G350-24 T-L Intermediate –50 °C

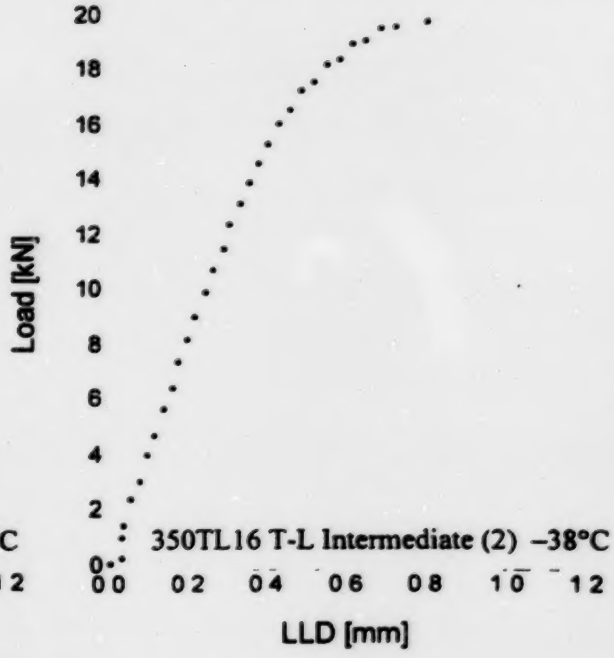

Load [kN]
LLD [mm]
350X-7 T-L Intermediate (2) –38°C


Load [kN]
LLD [mm]
350X-8 T-L Intermediate (2) –38°C


Load [kN]
LLD [mm]
350X-9 T-L Intermediate (2) –38°C


Load [kN]
LLD [mm]
350X-10 T-L Intermediate (2) –38°C

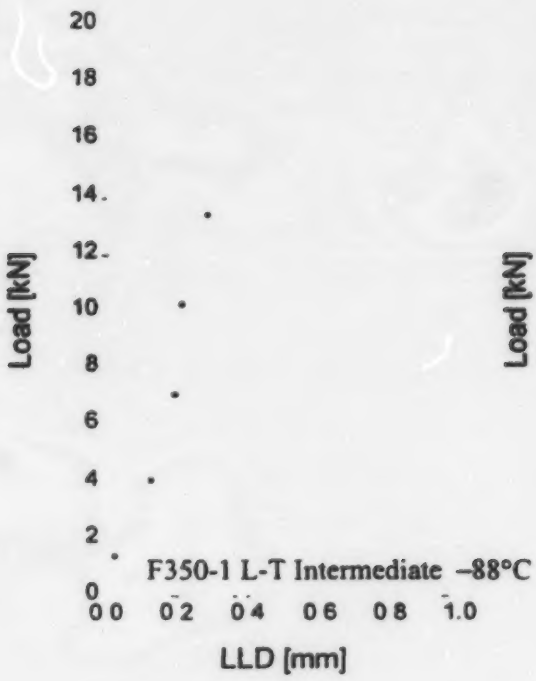

Load [kN]
LLD [mm]
350TL16 T-L Intermediate (2) –38°C

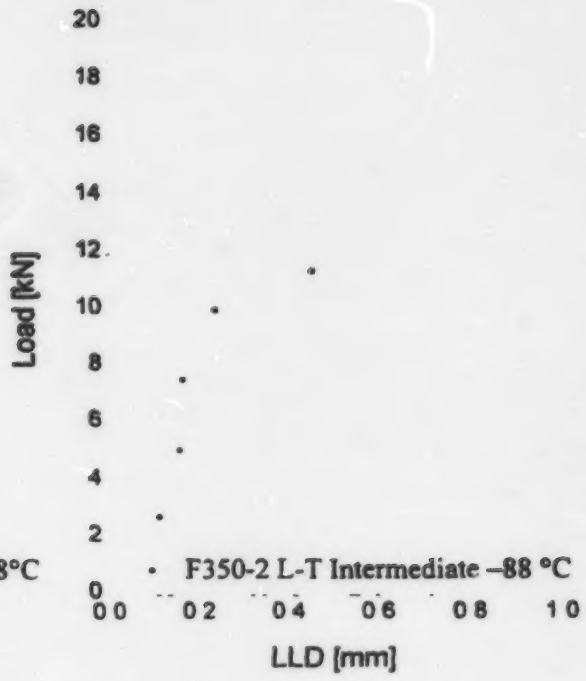

Load [kN]
LLD [mm]
350TL16 T-L Intermediate (2) –38°C

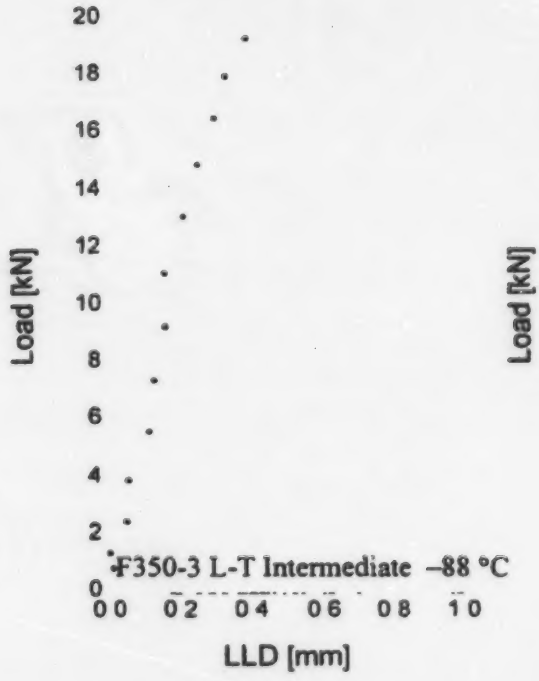
Appendix E

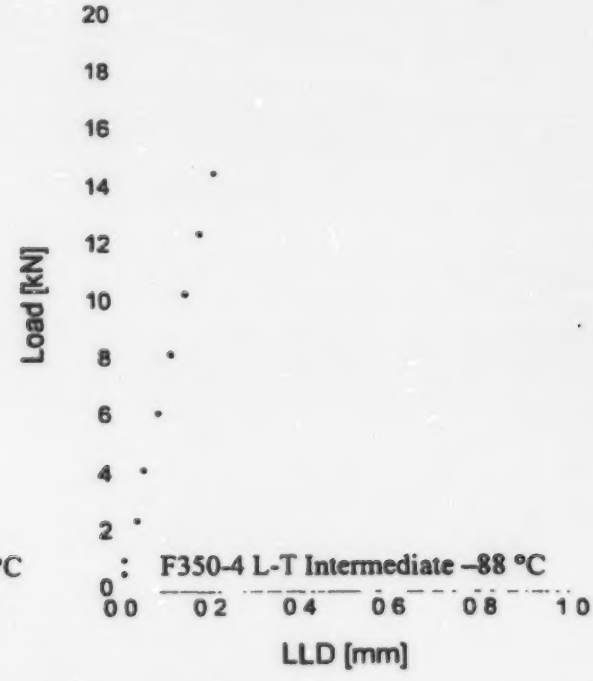
K_{Jc} Load-Load Line Displacement Curves

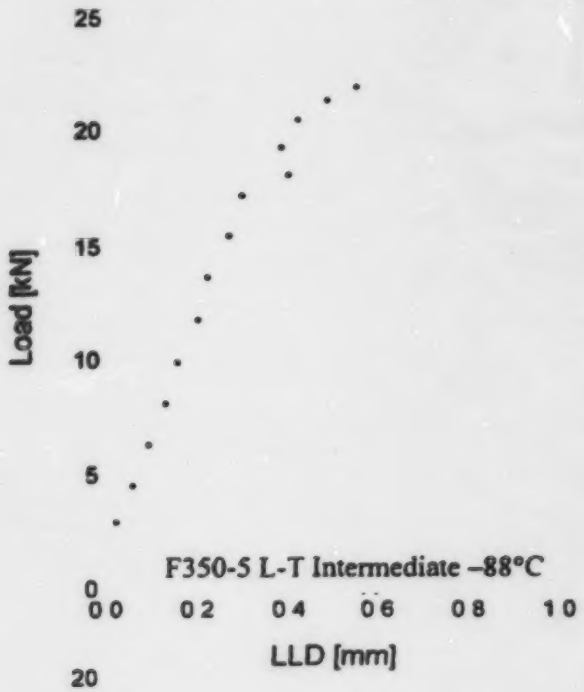
350WT Plate
L-T Orientation
Intermediate Loading Rate

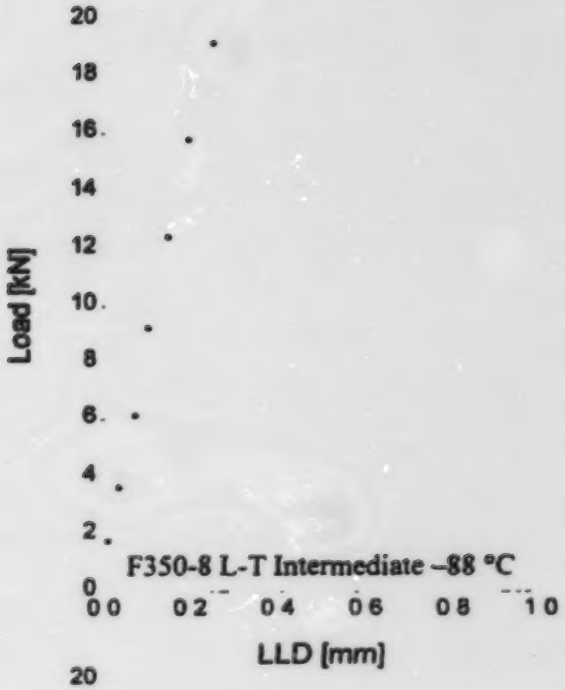

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
00 02 04 06 08 1.0
LLD [mm]
F350-1 L-T Intermediate –88°C

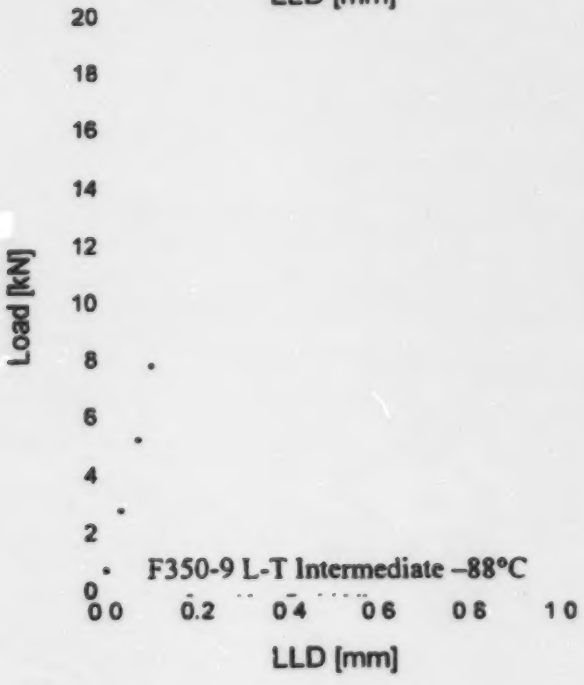

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
00 02 04 06 08 10
LLD [mm]
F350-2 L-T Intermediate –88 °C

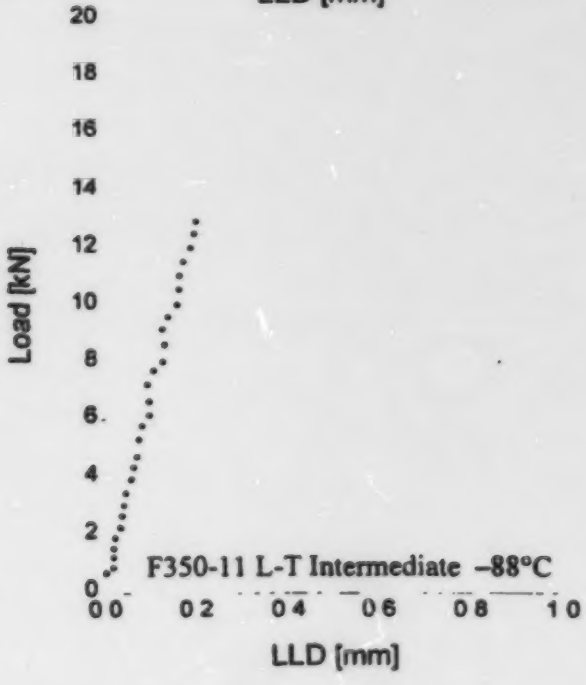

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
00 02 04 06 08 10
LLD [mm]
F350-3 L-T Intermediate –88 °C

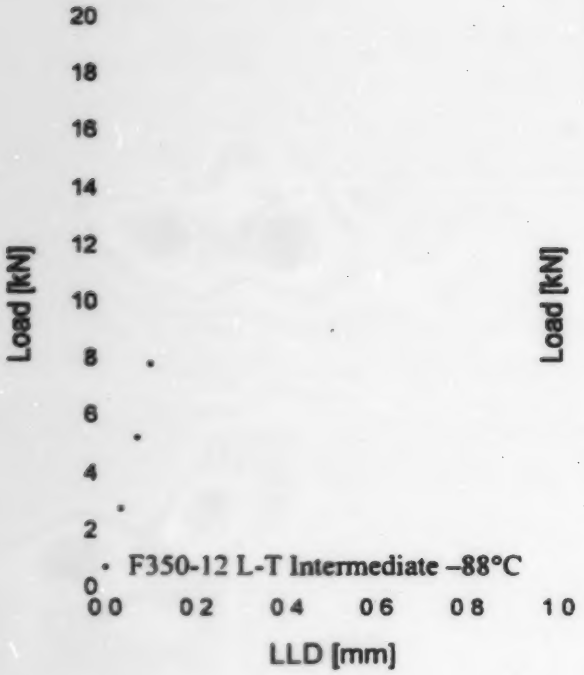

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
00 02 04 06 08 10
LLD [mm]
F350-4 L-T Intermediate –88 °C

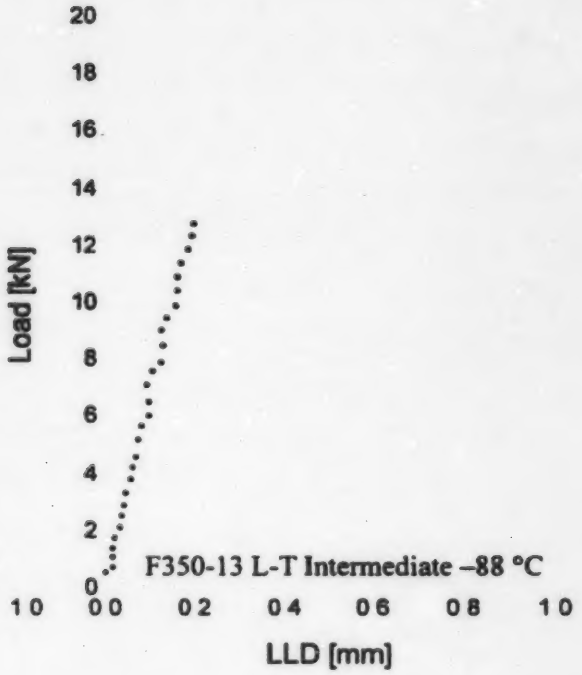

Load [kN]
LLD [mm]
F350-5 L-T Intermediate –88°C

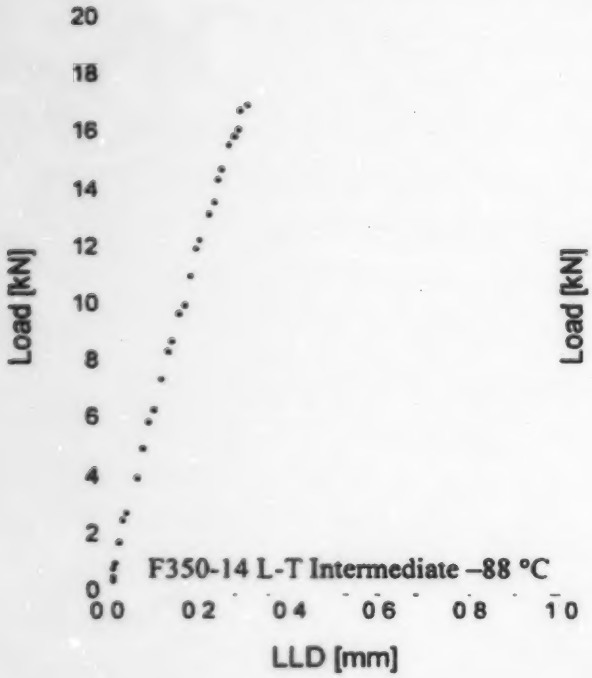

Load [kN]
LLD [mm]
F350-8 L-T Intermediate –88 °C

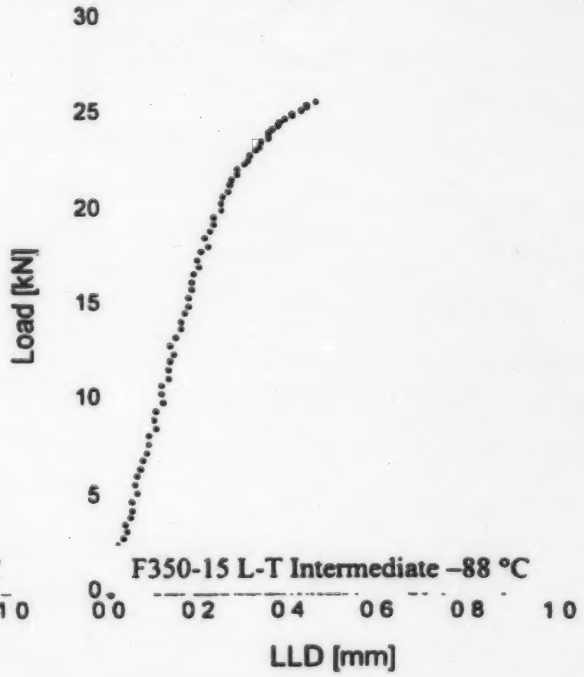

Load [kN]
LLD [mm]
F350-9 L-T Intermediate –88°C

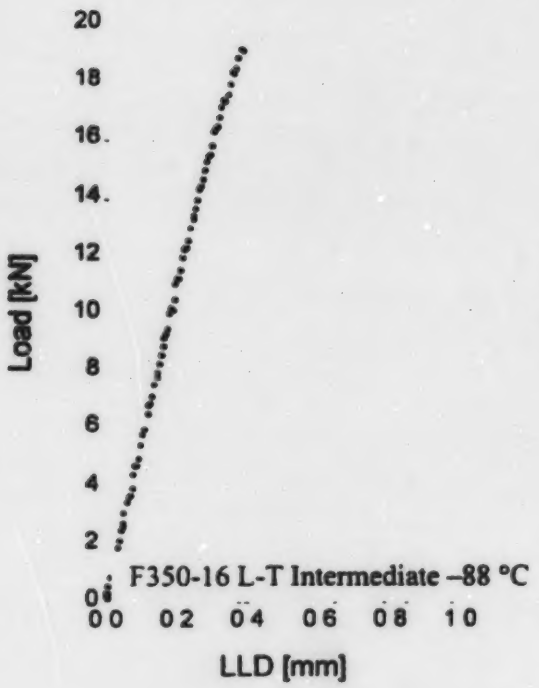

Load [kN]
LLD [mm]
F350-11 L-T Intermediate –88°C

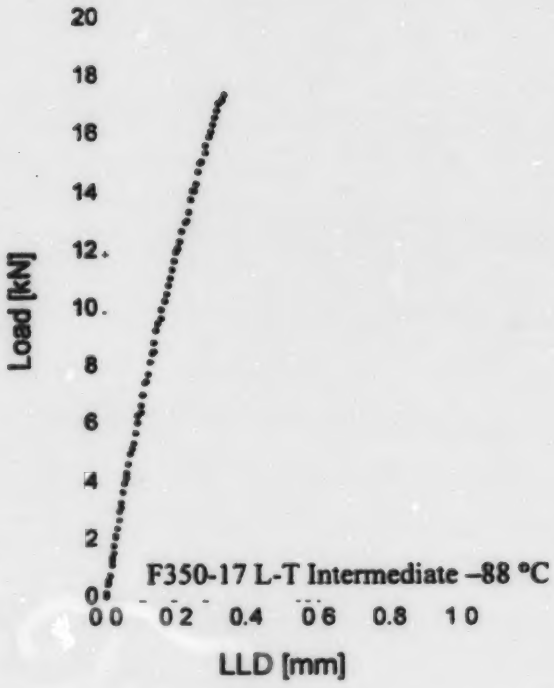

Load [kN]
LLD [mm]
F350-12 L-T Intermediate –88°C


Load [kN]
LLD [mm]
F350-13 L-T Intermediate –88 °C


Load [kN]
LLD [mm]
F350-14 L-T Intermediate –88 °C


Load [kN]
LLD [mm]
F350-15 L-T Intermediate –88 °C

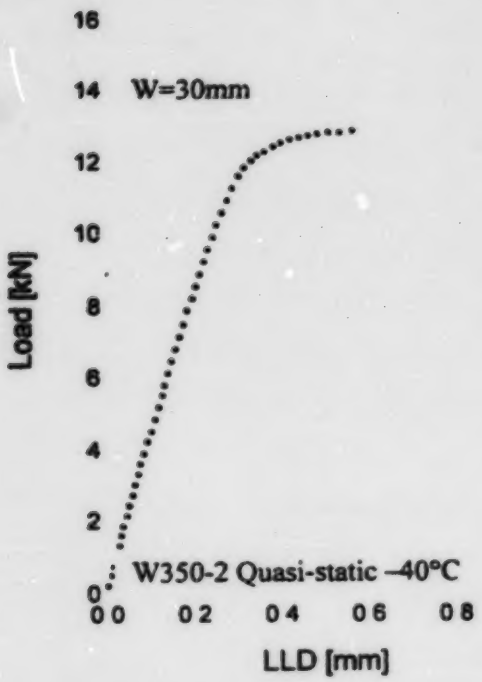

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
F350-16 L-T Intermediate –88 °C
00 02 04 06 08 10
LLD [mm]

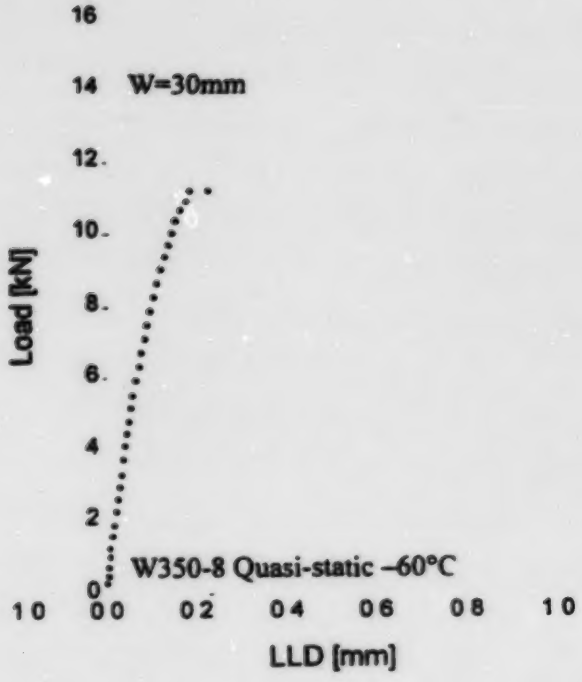

Load [kN]
20
18
16
14
12
10
8
6
4
2
0
F350-17 L-T Intermediate –88 °C
00 02 0.4 06 0.8 10
LLD [mm]

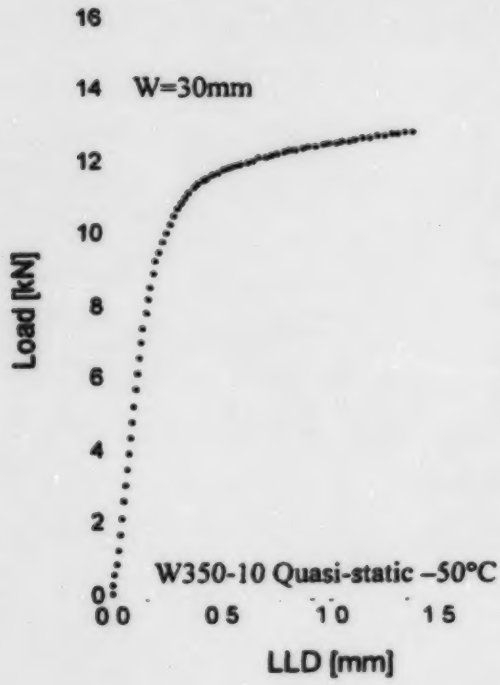
Appendix F

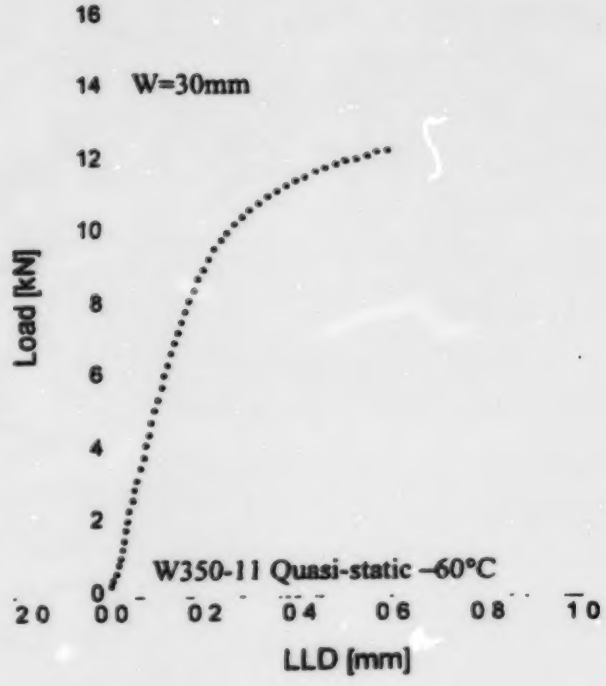
K_{Jc} Load-Load Line Displacement Curves

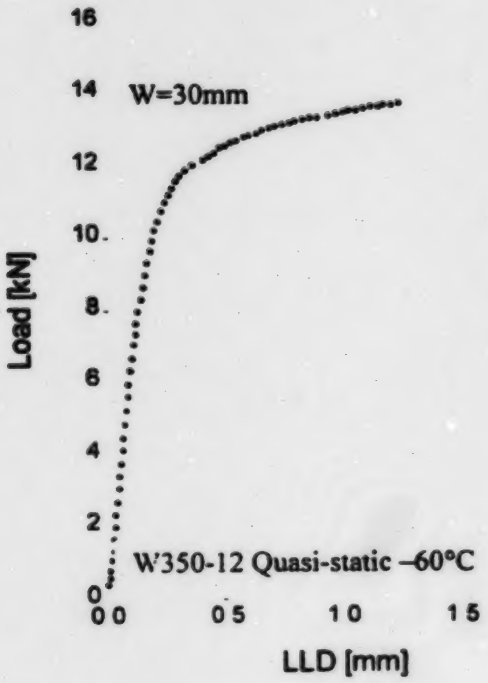
350WT Weld
Quasi Static Loading Rate

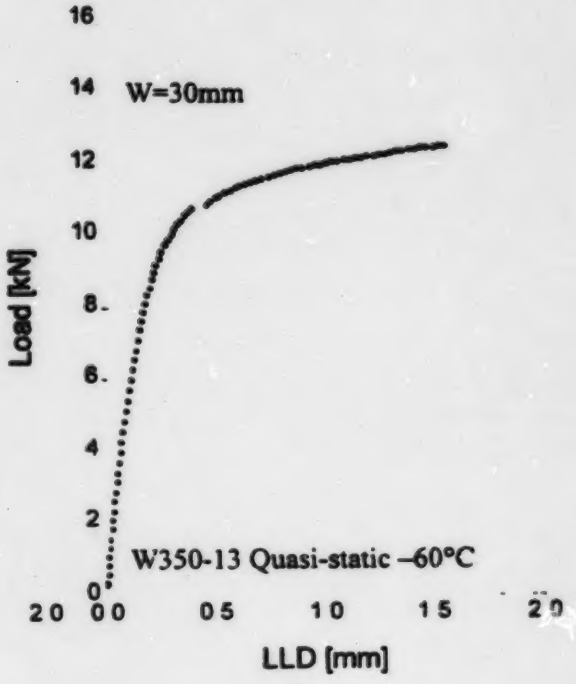

W=30mm
W350-2 Quasi-static –40°C
Load [kN]
LLD [mm]

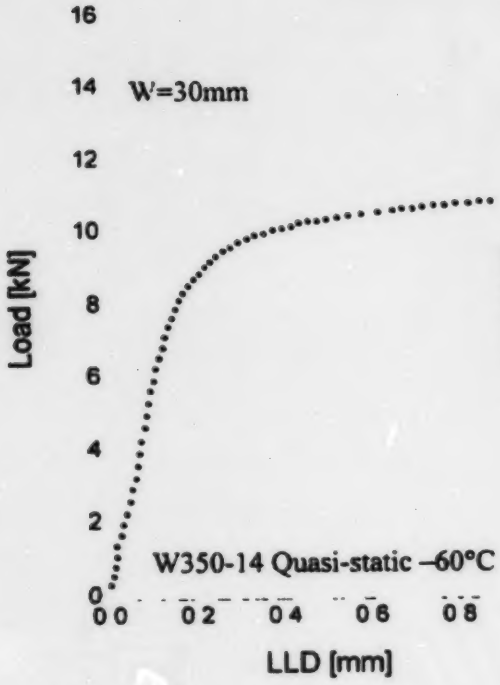

W=30mm
W350-8 Quasi-static –60°C
Load [kN]
LLD [mm]

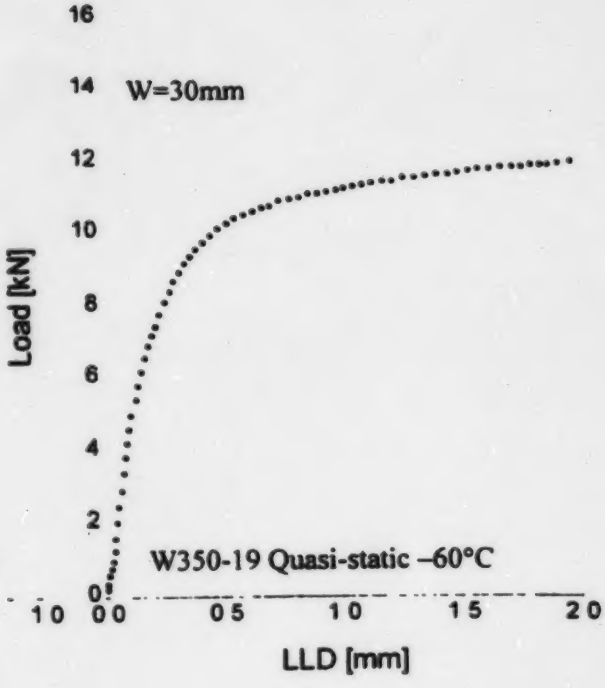

W=30mm
W350-10 Quasi-static –50°C
Load [kN]
LLD [mm]

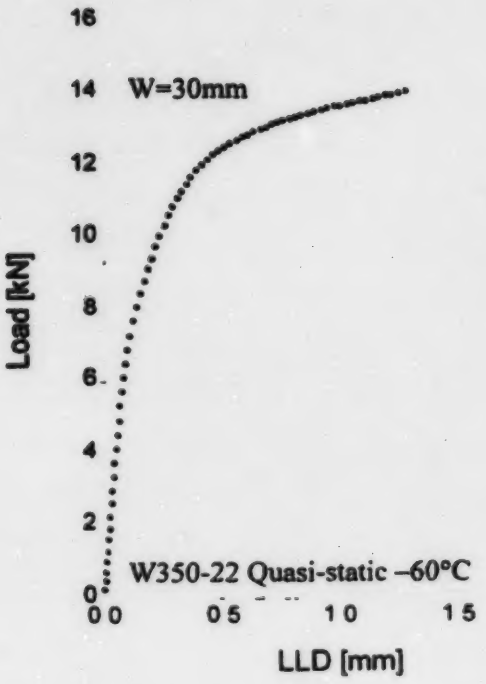

W=30mm
W350-11 Quasi-static –60°C
Load [kN]
LLD [mm]

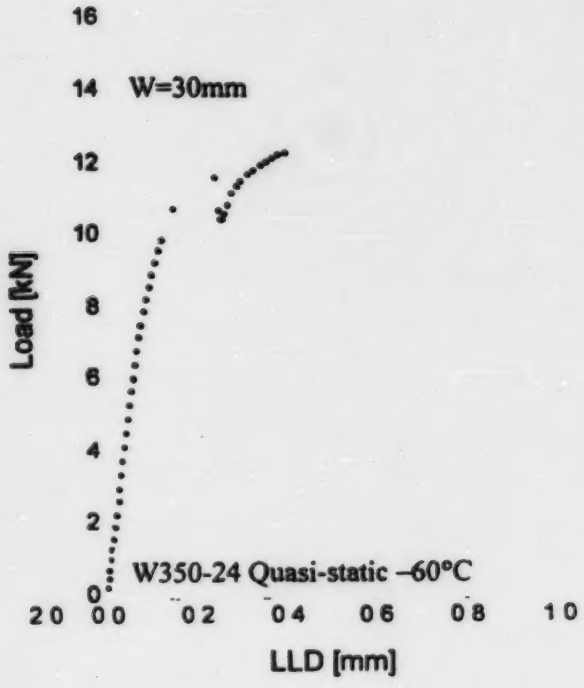

W=30mm
W350-12 Quasi-static –60°C
Load [kN]
LLD [mm]

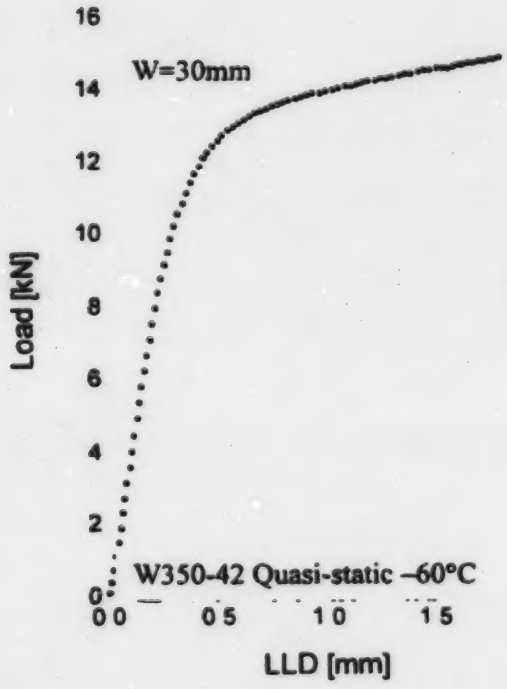

W=30mm
W350-13 Quasi-static –60°C
Load [kN]
LLD [mm]

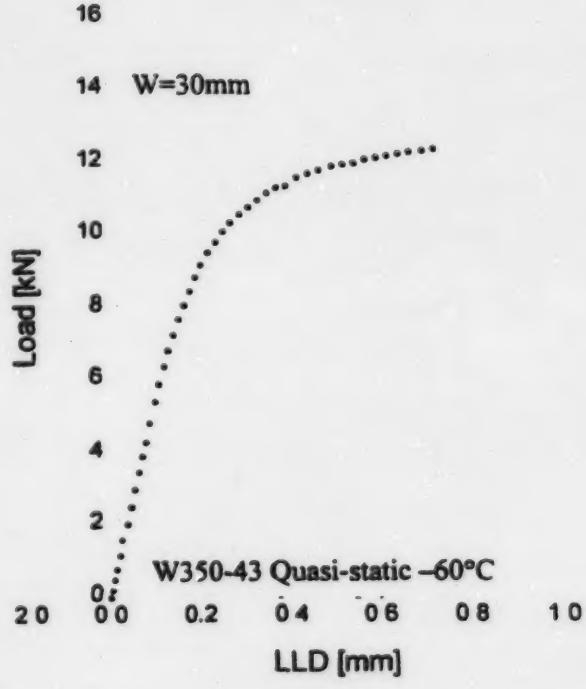

W=30mm
W350-14 Quasi-static –60°C
Load [kN]
LLD [mm]

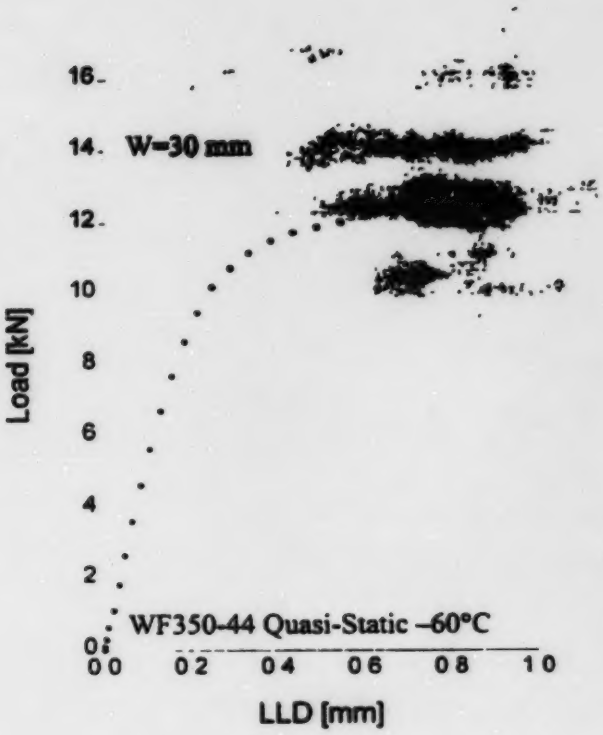

W=30mm
W350-19 Quasi-static –60°C
Load [kN]
LLD [mm]

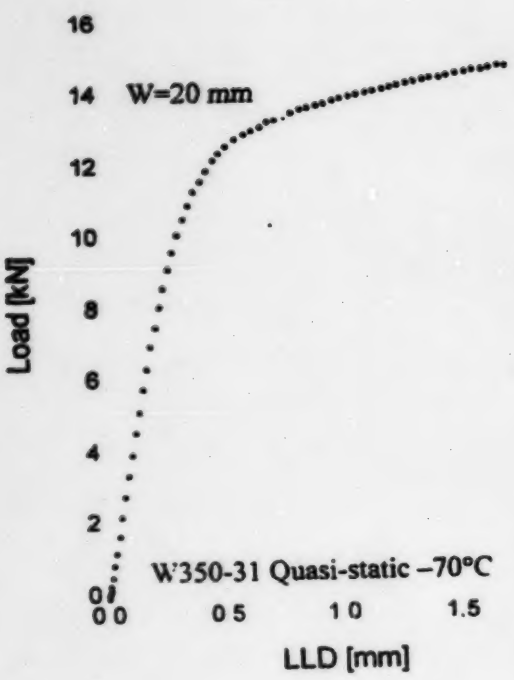

W=30mm
W350-22 Quasi-static –60°C
Load [kN]
LLD [mm]

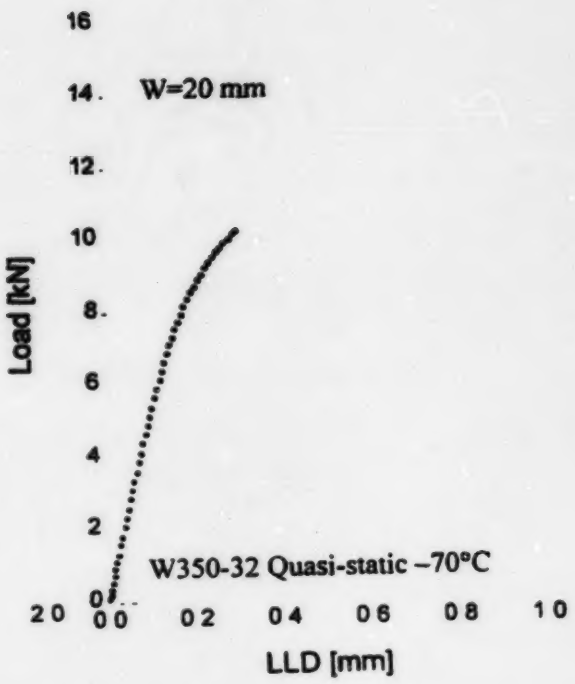

W=30mm
W350-24 Quasi-static –60°C
Load [kN]
LLD [mm]

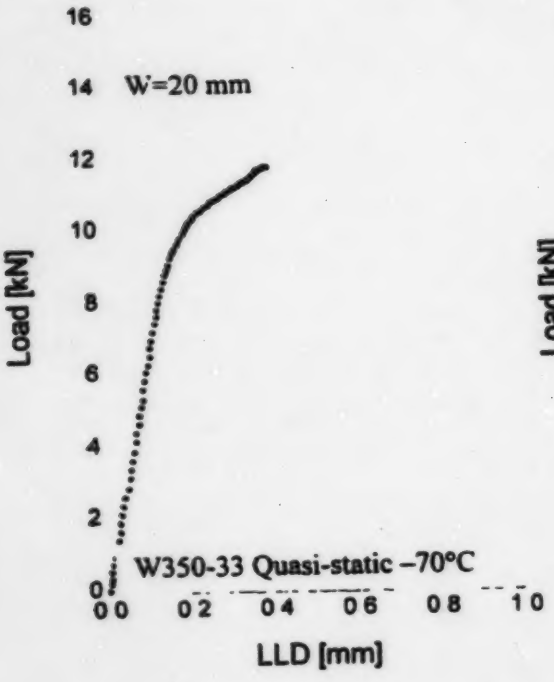

W=30mm
W350-42 Quasi-static –60°C
Load [kN]
LLD [mm]

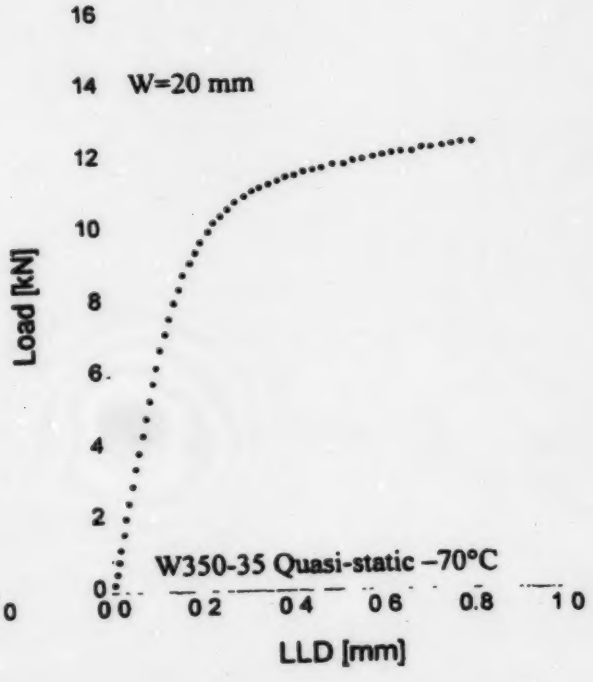

W=30mm
W350-43 Quasi-static –60°C
Load [kN]
LLD [mm]

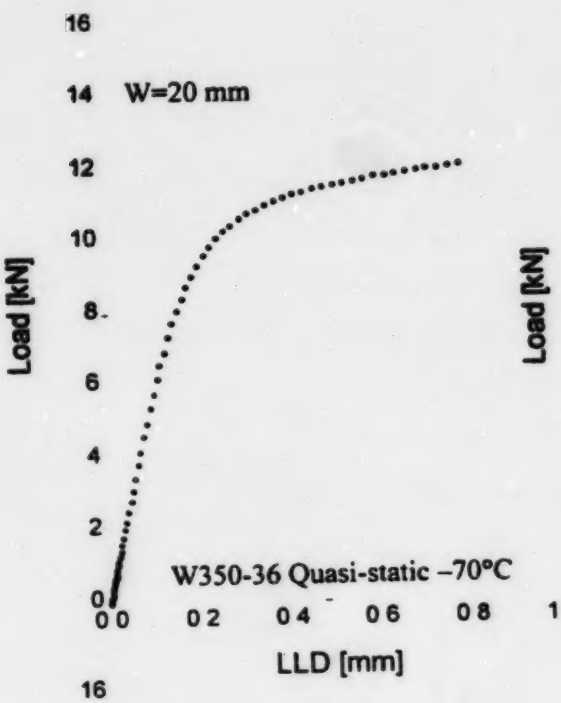

16
14
12
10
8
6
4
2
0
W=30 mm
Load [kN]
WF350-44 Quasi-Static –60°C
00
02
04
06
08
10
LLD [mm]

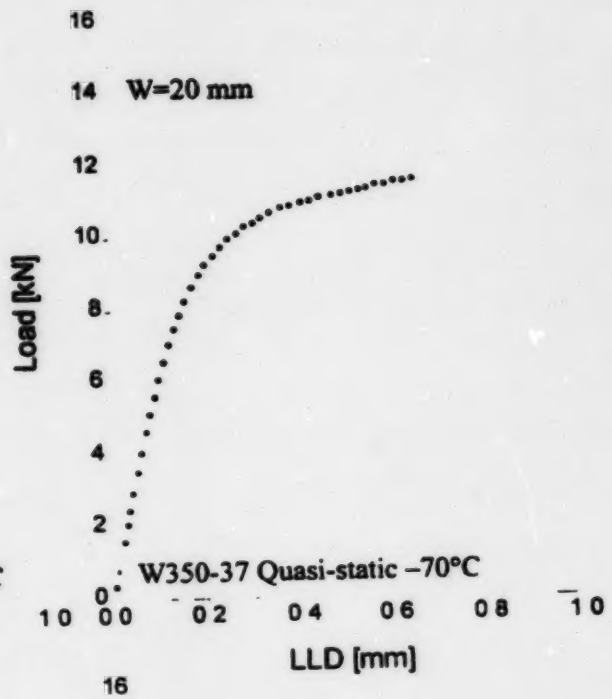

W=20 mm
W350-31 Quasi-static –70°C
Load [kN]
LLD [mm]
16
14
12
10
8
6
4
2
0
00
05
10
1.5

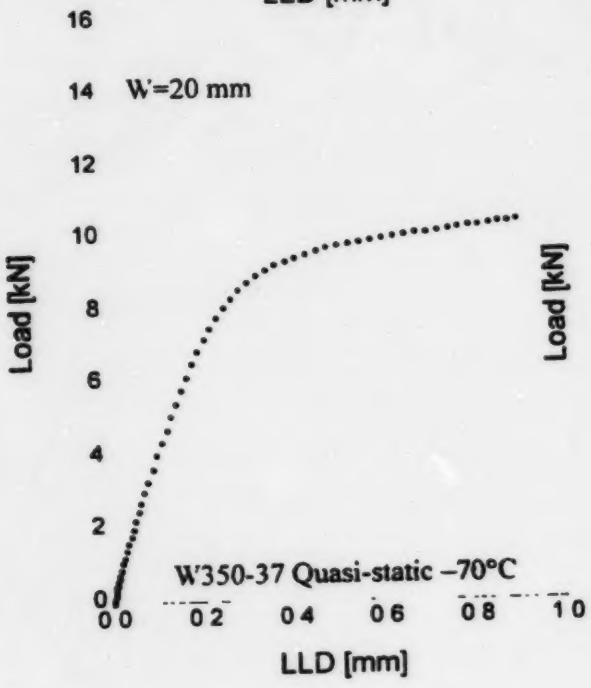

W=20 mm
W350-32 Quasi-static –70°C
Load [kN]
LLD [mm]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
10

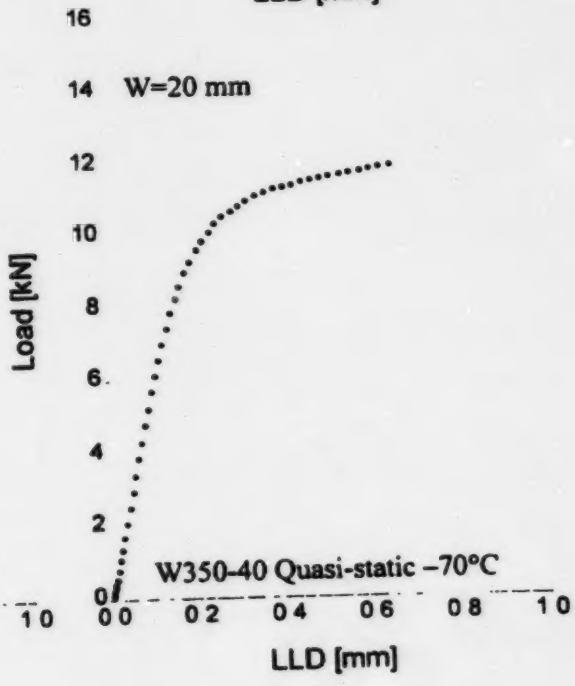

W=20 mm
W350-33 Quasi-static –70°C
Load [kN]
LLD [mm]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
10


W=20 mm
W350-35 Quasi-static –70°C
Load [kN]
LLD [mm]
16
14
12
10
8
6
4
2
0
00
02
04
06
0.8
10


W=20 mm
Load [kN]
LLD [mm]
W350-36 Quasi-static –70°C


W=20 mm
Load [kN]
LLD [mm]
W350-37 Quasi-static –70°C

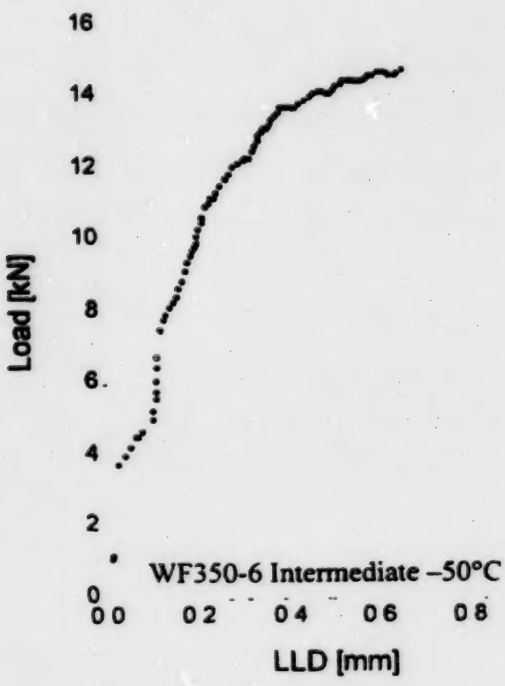

W=20 mm
Load [kN]
LLD [mm]
W350-37 Quasi-static –70°C

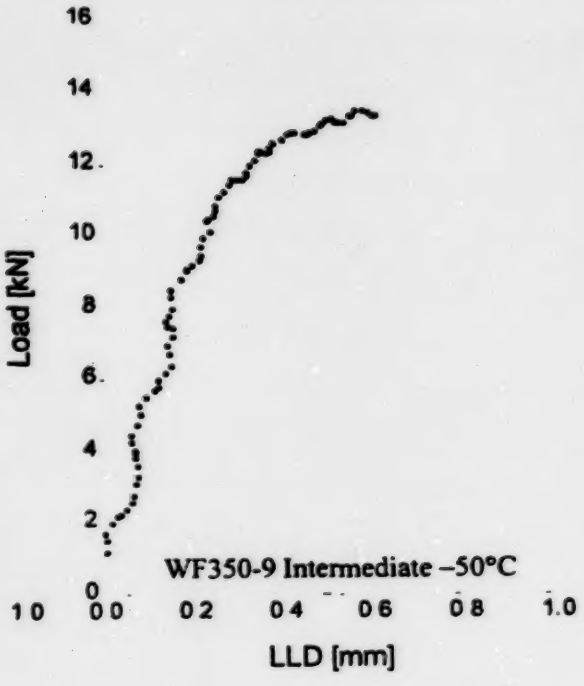

W=20 mm
Load [kN]
LLD [mm]
W350-40 Quasi-static –70°C

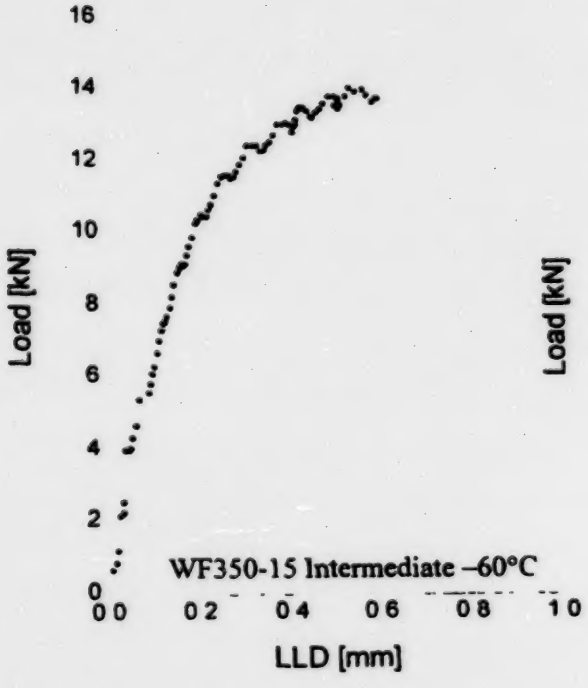
Appendix G

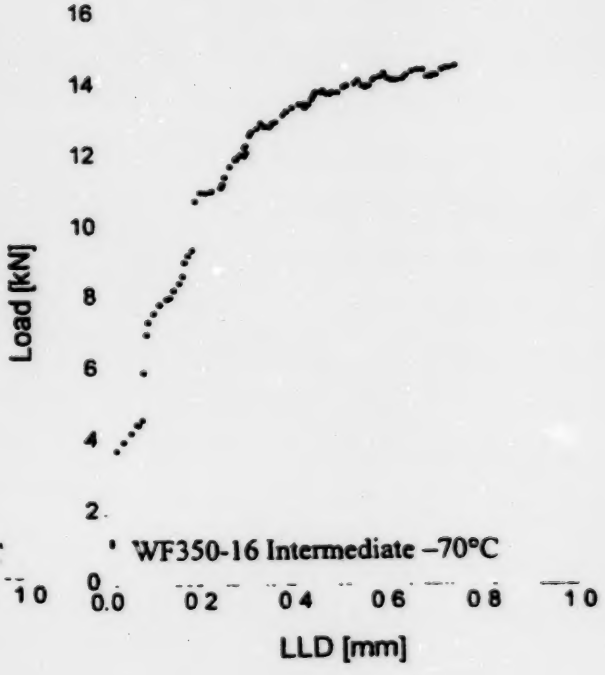
K_{Jc} Load-Load Line Displacement Curves

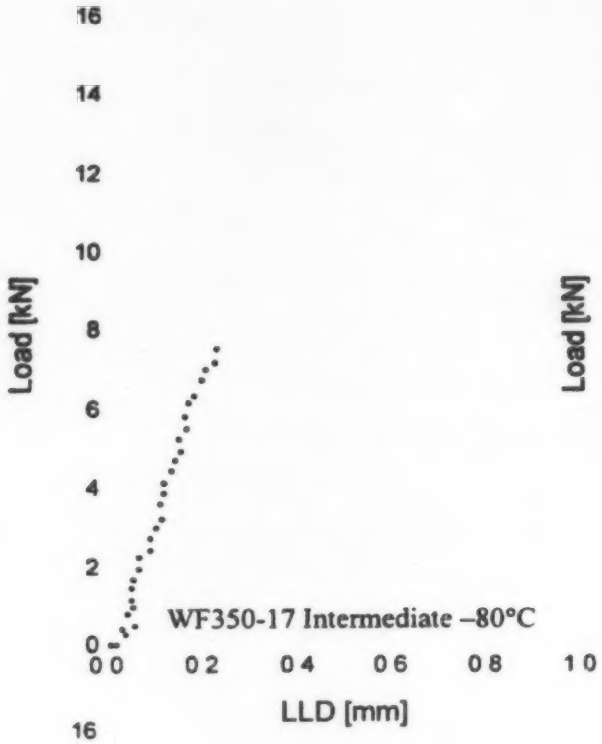
350WT Weld
IntermediateLoading Rate

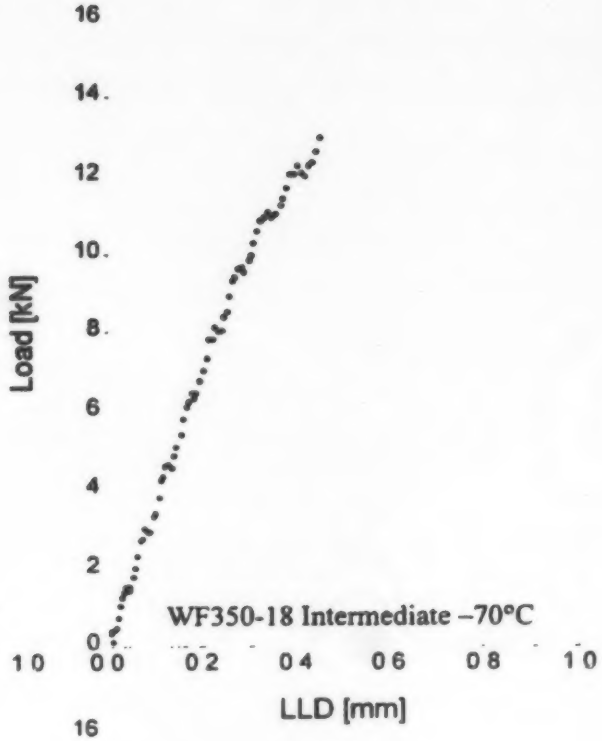

Load [kN]
LLD [mm]
WF350-6 Intermediate –50°C

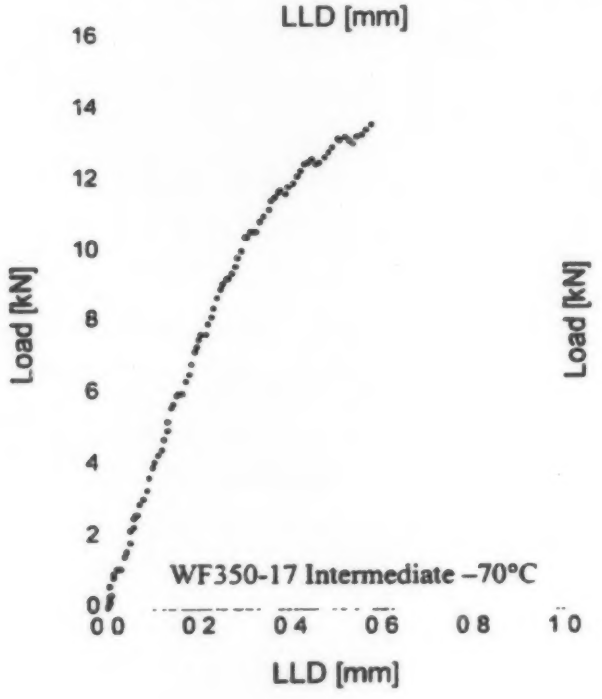

Load [kN]
LLD [mm]
WF350-9 Intermediate –50°C

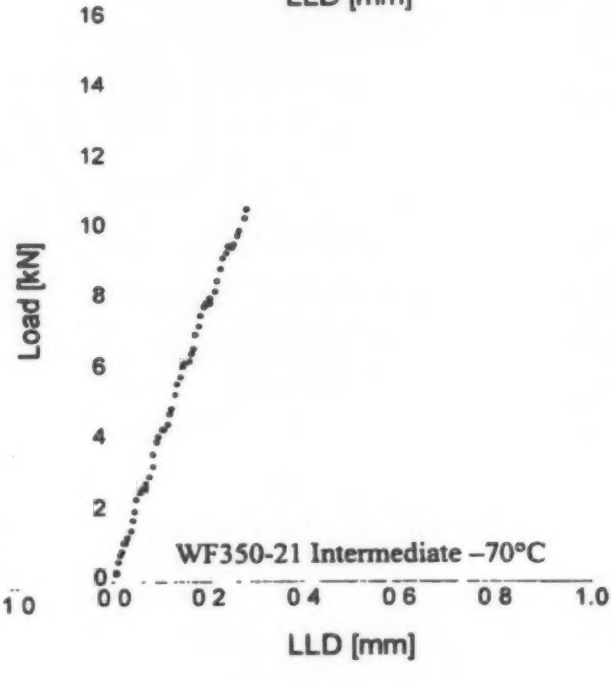

Load [kN]
LLD [mm]
WF350-15 Intermediate –60°C

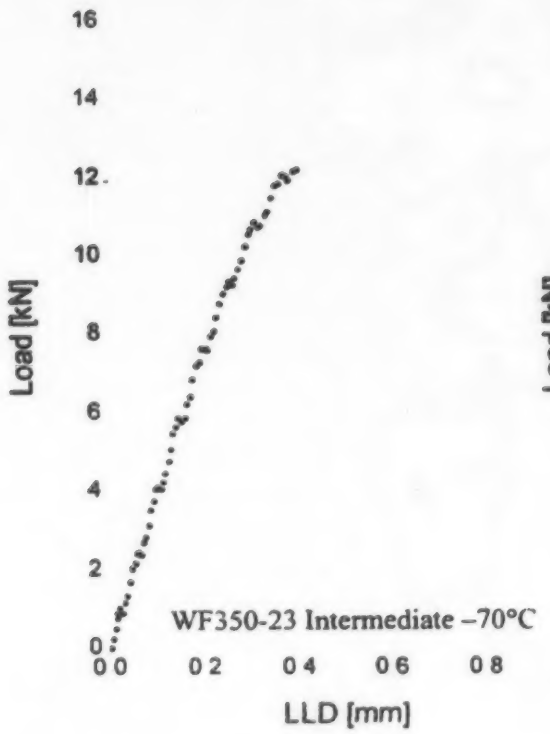

Load [kN]
LLD [mm]
WF350-16 Intermediate –70°C

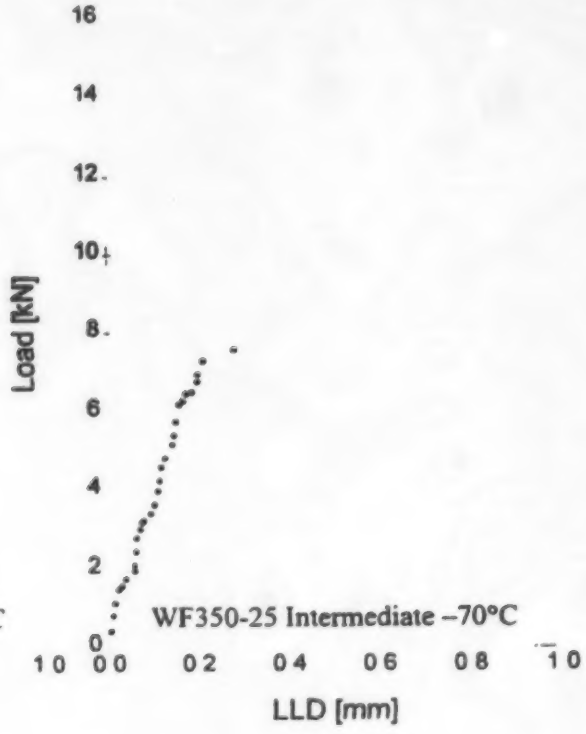

Load [kN]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
10
LLD [mm]
WF350-17 Intermediate –80°C

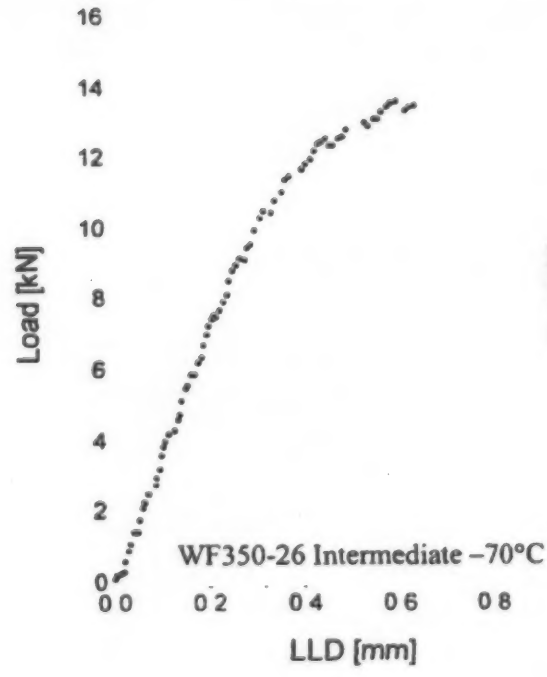

Load [kN]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
10
LLD [mm]
WF350-18 Intermediate –70°C

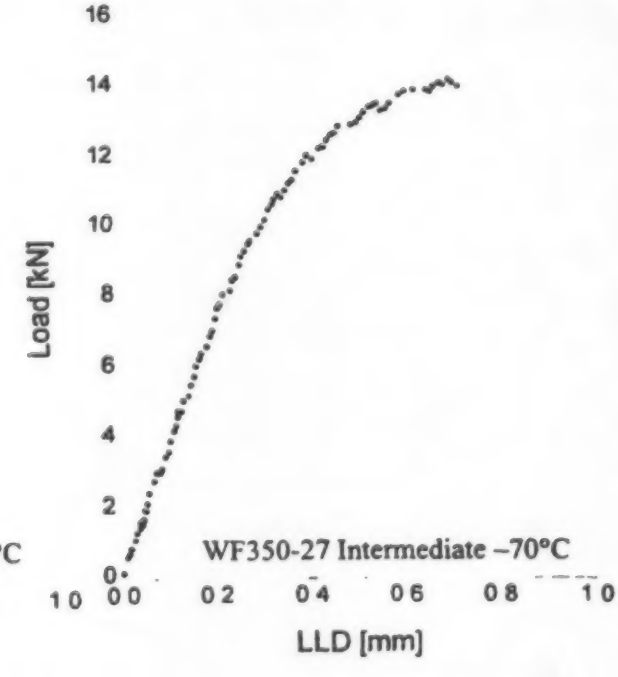

Load [kN]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
10
LLD [mm]
WF350-17 Intermediate –70°C


Load [kN]
16
14
12
10
8
6
4
2
0
00
02
04
06
08
1.0
LLD [mm]
WF350-21 Intermediate –70°C


Load [kN]
LLD [mm]
WF350-23 Intermediate –70°C


Load [kN]
LLD [mm]
WF350-25 Intermediate –70°C


Load [kN]
LLD [mm]
WF350-26 Intermediate –70°C


Load [kN]
LLD [mm]
WF350-27 Intermediate –70°C

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D.A. Hull

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The DREA Dockyard Laboratory Pacific (DL(P)) has an on-going requirement to determine the fracture toughness of ship steels and welds in the ductile to brittle transition temperature range. ASTM Test Method E1921-97 "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range" can be used to generate transition master curves.

CSA G21 350WT is a ferritic steel used extensively in the hulls of the Canadian Navy's Halifax class frigates. An earlier contract demonstrated that valid results could be obtained from 350WT L-T oriented specimens using the ASTM test method. This program was subsequently expanded to investigate the effect of plate orientation (L-T and T-L) and loading rates (quasi-static and intermediate) on both 350WT plate and welds. This work was supplemented by experiments at DL(P) using a drop tower to achieve high deformation rates The test program was very successful in quantifying the fracture toughness over the temperature range of interest Both the plate and submerged arc weld are very tough, and have very low reference temperatures, suggesting that there is a high resistance to brittle fracture in this material. This data will be useful for damage assessment and fitness-for-purpose assessments in repair situations

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Toughness
Reference Temperature
Transition
Master Curve
Ship Plate

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